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THESIS

A STUDY OF DIRECTIONAL AND FREQUENCY
PROPERTIES OF SHADED AND PHASED
SIMPLE ARRAYS

by

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December 1986

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Five computer models are presented and used in investigating the directional and frequency properties of shaded and phased doublet, triplet and quadruplet arrays. Comparisons associated with parameters such as wavelength, inter-source distance, source strength, and phase difference are examined.

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A Study of Directional and Frequency Properties of Shaded and Phased Simple Arrays

by

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ABSTRACT

Computer programs are designed to calculate and display beam patterns in both two and three dimensions. Graphical presentation and evaluation in three-dimensions are difficult and important problems.

Five computer models are presented and used in investigating the directional and frequency properties of shaded and phased doublet, triplet and quadruplet arrays. Comparisons associated with parameters such as wavelength, inter-source distance, source strength, and phase difference are examined.

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I. INTRODUCTION

Not only is the physical interpretation of the radiation of the acoustic waves in more than one dimension complex, but the effects of varying frequency and shading are hard to visualize when considering directionality and frequency properties. As Wood implied in his book, A Textbook of Sound [Ref. 1: p.449], the directional factor is very important in many acoustic applications such as speech, hearing and array design.

The simplest array one can consider is the beam pattern of a dipole radiating in two dimensions. References to the case of the simple dipole can be found in virtually every textbook in acoustics. For a fairly recent example, see Malecki's book [Ref. 2: p.199]. Currently, the mathematical modeling of the simple acoustic arrays has been enhanced with the advent of the sophisticated computer software. Specifically, Ziomek [Ref. 3: p.138] and, Embleton and Thiessen [Ref. 4: p.1124] have investigated N point source arrays, considering both amplitude and phase weighting. Although the mathematics and computer hardware exist, the visualization of the three-dimensional aspects of these arrays is difficult. By use of the computer graphics software the ability to interpret the significance of shading and phasing can be fully developed [Refs. 5,6].

To date, visualization of the three-dimensional beam pattern has been needed to understand the directional factor. Numerical computer output was essential to draw three-dimensional graphs. By changing two parameters (in three-dimensions, those could be x and y or θ and φ, etc.), different generated values of the beam pattern, F, are obtained.

One computer program to visualize the beam pattern in three-dimensions (P3D) and four computer programs to read values in detail (2DICIR, 2DPCIR, 2DIFIX, 2DPFIX) were written. These computer models predict the directional factor and overall beam pattern with or without differences in the source strengths, inter-source distances, and phases of the elements of the arrays.

Typical geometry for the beam pattern prediction is shown in Figure 2.3 on page 16.

The following definitions apply and will be used throughout:

I = source strength of the first source (source 1)

A = source strength of source 2

B = source strength of source 3

C = source strength of source 4

D_1 = distance from the geometrical center to source 1

D_2 = distance from the geometrical center to source 2

D_3 = distance from the geometrical center to source 3

D_4 = distance from the geometrical center to source 4

φ_2 = phase difference between source 2 and source 1

φ_3 = phase difference between source 3 and source 1

φ_4 = phase difference between source 4 and source 1

θ = angle measured from the z axis toward the x-y plane

Φ = angle measured counterclockwise in the x-y plane starting from the x axis

k = wave number

w = angular frequency

R = distance from the geometrical center to a certain point in space

H = directional factor

F = beam pattern = $20\log_{10}|H|$ or $10\log_{10}H^2$ expressed in dB

All distances are measured from the origin of the coordinate system to the sources along the x and y axes. Phase differences are based upon the phase of the first source, which is assumed to be zero.

The goal of this thesis is to develop a convenient methodology for the investigation of the functional dependency of the directional factor on the source amplitudes (A, B and C), distances from the origin (D_1, D_2, D_3 and D_4), phase differences (φ_2, φ_3 and φ_4), and θ and Φ as demonstrated by the five programs: P3D, 2DICIR, 2DPCIR, 2DIFIX, 2DPFIX.

II. THEORY

A spatial configuration of simple sources, either discrete or distributed, each with its own complex source strength, can be used to represent the quadruplet source case. The pressure at a field point is the sum of pressures produced by the individual sources [Ref. 7: p.169]. Before we develop the quadruplet source case, the acoustic doublet case needs to be described to provide a background for the more complicated quadruplet case.

A. DOUBLET SOURCES

A doublet source consists of two point sources of strengths of 1 and A, separated from the origin, by distances D_1 and D_2 and vibrating at the same frequency but with a phase difference φ.

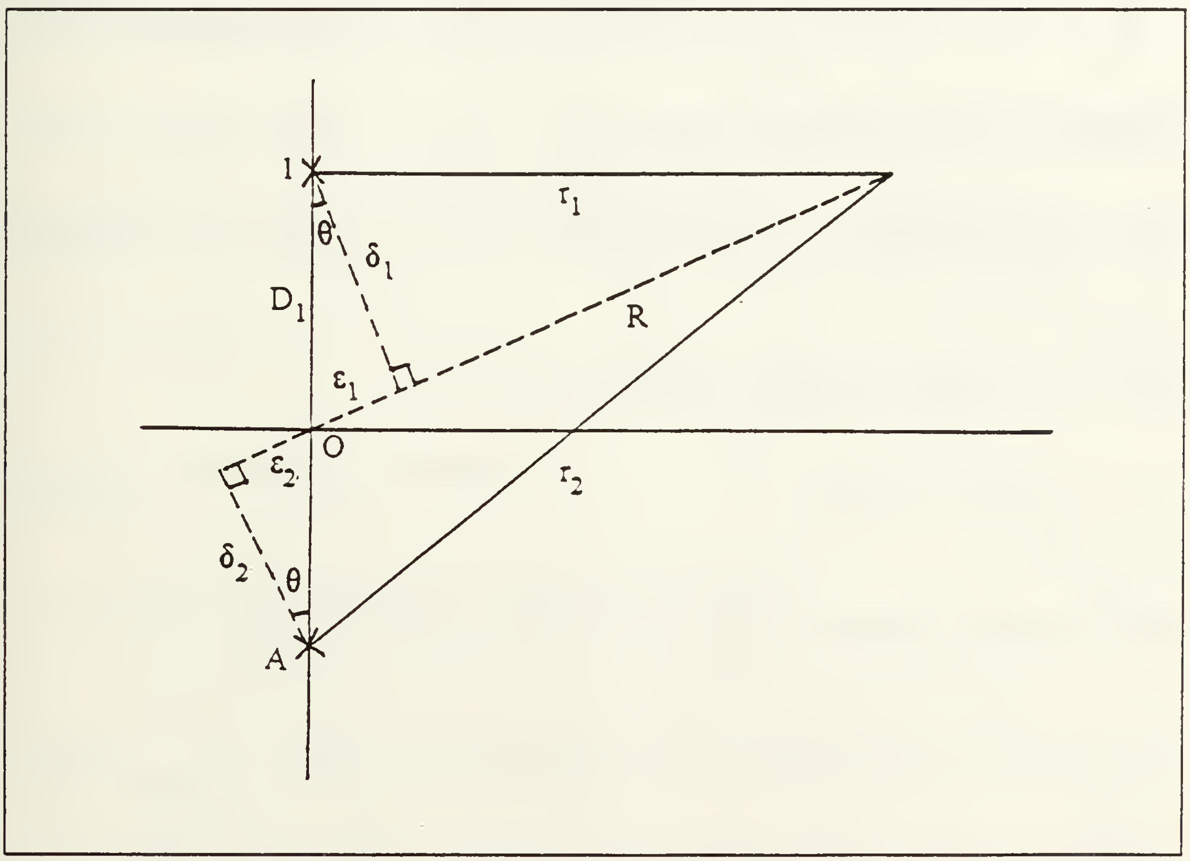

Figure 2.1 Geometry of doublet.

From the geometry shown in Figure 2.1, we have

$$\cos\theta = \delta_1/D_1, \tag{2.1}$$
$$\sin\theta = \varepsilon_1/D_1, \tag{2.2}$$

$$r_1 = \sqrt{(R - \varepsilon_1)^2 + \delta_1^{\,2}}$$
$$= \sqrt{(R - D_1\sin\theta)^2 + (D_1\cos\theta)^2}, \tag{2.3}$$
$$\frac{r_1}{R} = \sqrt{(1 - D_1\sin\theta/R)^2 + (\delta_1\cos\theta/R)^2}. \tag{2.4}$$
$$\sin\theta = \varepsilon_2/D_2, \tag{2.5}$$
$$\cos\theta = \delta_2/D_2, \tag{2.6}$$
$$r_2 = \sqrt{(R + \varepsilon_2)^2 + \delta_2^{\,2}}$$
$$= \sqrt{(R + D_2\sin\theta)^2 + (D_2\cos\theta)^2}, \tag{2.7}$$
$$\frac{r_2}{R} = \sqrt{(1 + D_2\sin\theta/R)^2 + (\delta_2\cos\theta/R)^2}. \tag{2.8}$$

The pressure at point (R,θ) due to source 1 is

$$P_1 = \frac{1}{r_1} e^{j(wt - kr_1)} \tag{2.9}$$

where w is the angular frequency. That due to source 2 is

$$P_2 = \frac{A}{r_2} e^{j(wt - kr_2 - \varphi)}. \tag{2.10}$$

The total acoustic pressure at point (R,θ) is then the sum of P_1 and P_2,

$$P = \frac{1}{R} e^{j(wt - kR)}\left\{ \frac{R}{r_1} e^{jk(R - r_1)} + \frac{AR}{r_2} e^{-j[k(r_2 - R) + \varphi]} \right\} \tag{2.11}$$

where R is the distance from the field point to the origin. From (2.4) and (2.8), we get

$$k(R - r_1) = kR(1 - r_1/R)$$

$$= kR[1 - \sqrt{(1 - D_1\sin\theta/R)^2 + (D_1\cos\theta/R)^2}\,], \tag{2.12}$$

$$k(r_2 - R) = kR(r_2/R - 1)$$

$$= kR[\sqrt{(D_2\sin\theta/R + 1)^2 + (D_2\cos\theta/R)^2} - 1\,]. \tag{2.13}$$

Therefore, equation (2.11) can be rewritten as

$$P = \frac{1}{R} e^{j(wt - kR)}\{ \frac{R}{r_1} e^{jkR[1 - \sqrt{(1 - D_1\sin\theta/R)^2 + (D_1\cos\theta/R)^2}\,]}$$

$$+ \frac{AR}{r_2} e^{-j[kR[\sqrt{(D_2\sin\theta/R + 1)^2 + (D_2\cos\theta/R)^2} - 1\,] + \varphi]}\}. \tag{2.14}$$

In the most frequently encountered cases, the observation of the pressure is made at distances greater than the separation of the sources. Therefore, it will be useful to derive the far field ($R >> (D_1 + D_2)$) pressure equation from the above equation (2.14). From the geometry shown in Figure 2.2, we have

$$\sin\theta = \varepsilon_1/D_1 = \varepsilon_2/D_2. \tag{2.15}$$

Therefore, $(R - r_1)$ and $(r_2 - R)$ can be replaced with $D_1\sin\theta$ and $D_2\sin\theta$. Also we have

$$\frac{R}{r_1} \sim \frac{R}{r_2} \sim 1 \tag{2.16}$$

so that the pressure equation becomes

$$P = \frac{1}{R} e^{j(wt - kR)}[e^{jkD_1\sin\theta} + Ae^{-j(kD_2\sin\theta + \varphi)}] \tag{2.17}$$

$$|P| = P(R)H(\theta) \tag{2.18}$$

where $P(R) = (1+A)/R$.

$$H(\theta) = \frac{1}{(1+A)} | e^{j(kD_1\sin\theta)} + Ae^{-j(kD_2\sin\theta + \varphi)} |. \tag{2.19}$$

This directivity factor, $H(\theta)$ can be written as

$$H(\theta) = \frac{1}{(1+A)} \{[\cos(kD_1\sin\theta) + A\cos(kD_2\sin\theta + \varphi)]^2 + [\sin(kD_1\sin\theta) - A\sin(kD_2\sin\theta + \varphi)]^2\}^{1/2}. \tag{2.20}$$

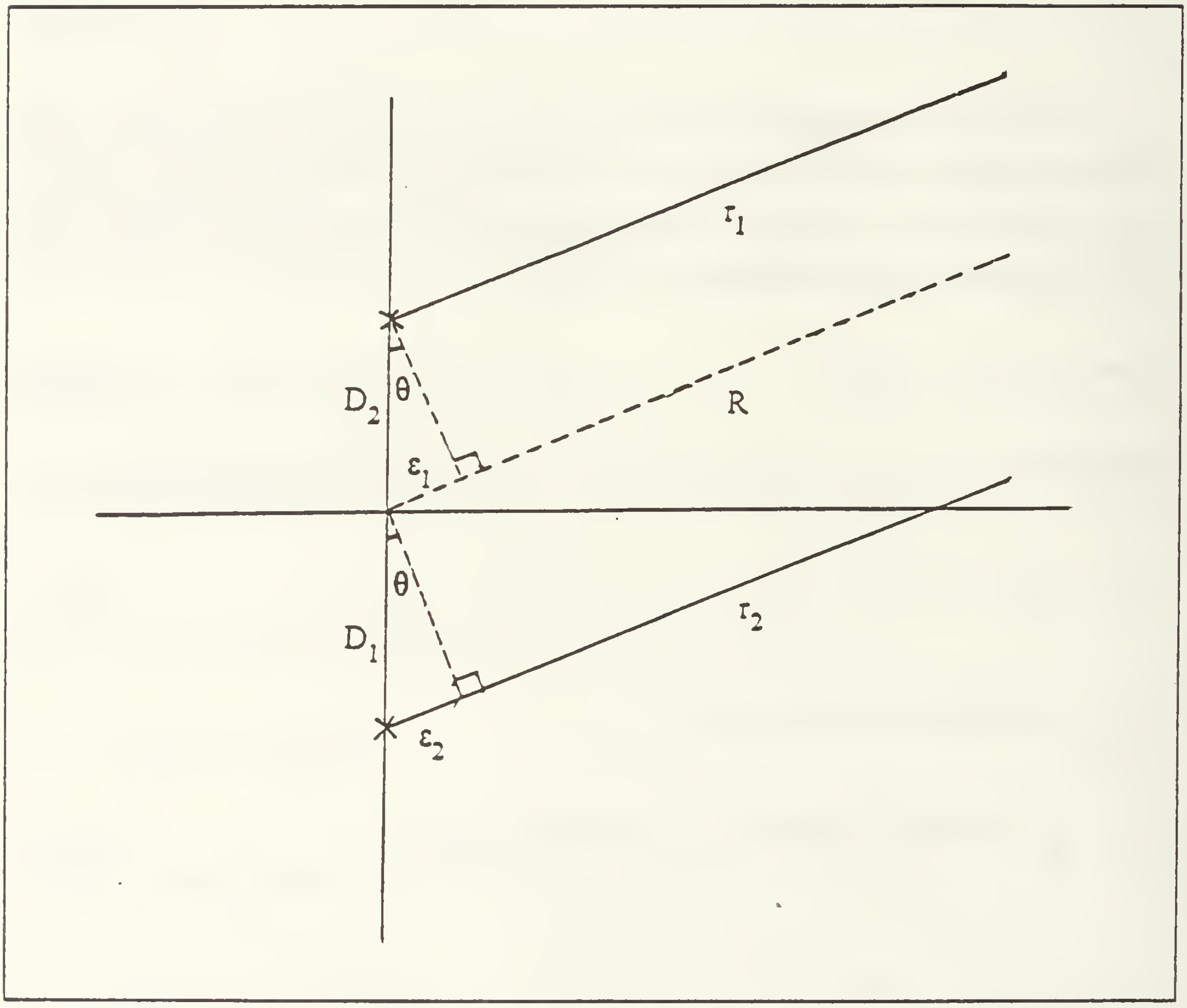

Figure 2.2 Geometry of doublet (far field).

B. QUADRUPLET SOURCES

Similarly, a quadruplet source case can be developed with four sources of strengths 1, A, B and C, separated from the origin, by distances D_1, D_2, D_3 and D_4 and vibrating at the same frequency with phase differences φ_2, φ_3 and φ_4 (Figure 2.3).

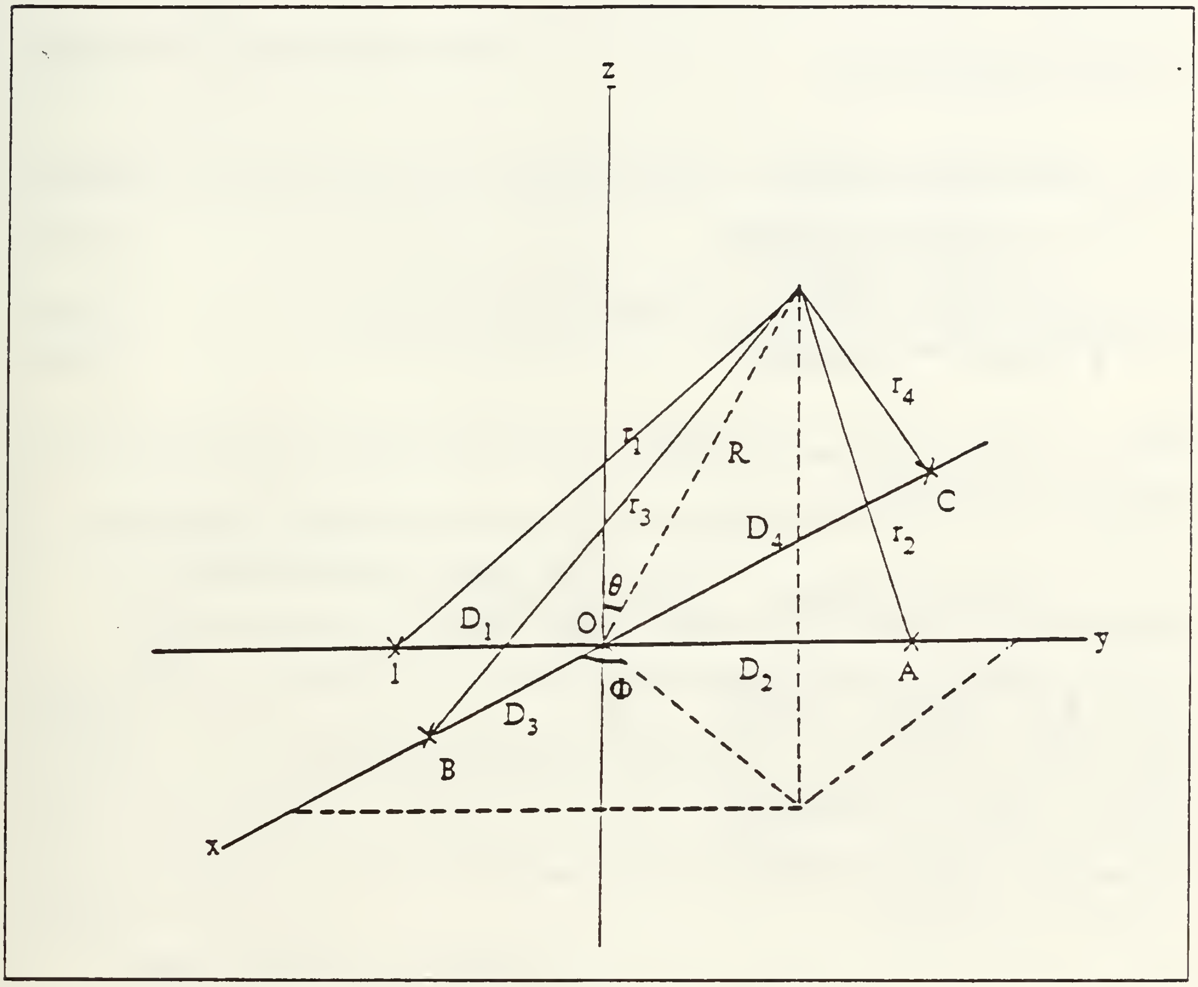

Figure 2.3 Geometry of quadruplet.

From the geometry shown in Figure 2.3, we have

$$x = R\sin\theta\cos\Phi, \tag{2.21}$$

$$y = R\sin\theta\sin\Phi, \tag{2.22}$$

$$z = R\cos\theta, \tag{2.23}$$

$$R = \sqrt{x^2+y^2+z^2} \tag{2.24}$$

where x, y, z are rectangular coordinates and R is the distance from the field point to the origin.
And then

$$r_1 = \sqrt{(y + D_1)^2 + x^2 + z^2}. \tag{2.25}$$

By Taylor's approximation

$$r_1 \sim R + D_1 y/R + D_1^2/2R. \tag{2.26}$$
$$r_1 - R = D_1 y/R = D_1 \sin\theta \sin\Phi, \tag{2.27}$$

$$r_2 = \sqrt{(y - D_2)^2 + x^2 + z^2} \sim R - D_2 y/R, \tag{2.28}$$
$$R - {}_2 = D_2 y/R = D_2 \sin\theta \sin\Phi \tag{2.29}$$

where R is much greater than D_1, and D_2.
Using the same approach

$$r_3 = \sqrt{(x - D_3)^2 + y^2 + z^2} = \sqrt{R^2 - 2D_3 x + D_3^2}$$
$$= R\sqrt{1 - (2D_3 x/R^2 - D_3^2/R^2)}\,. \tag{2.30}$$
$$r_3 \sim R[1 - (1/2)(2D_3 x/R^2 - D_3^2/R^2)] = R - D_3 x/R + D_3^2/2R, \tag{2.31}$$
$$R - r_3 = D_3 x/R = D_3 \sin\theta \cos\Phi \tag{2.32}$$

$$r_4 = \sqrt{(x + D_4)^2 + y^2 + z^2} \sim R + D_4\, x/R, \tag{2.33}$$
$$r_4 - R = D_4 \sin\theta \cos\Phi \tag{2.34}$$

where R is much greater than D_3, and D_4.
Therefore, the pressure at (R, θ, φ) is

$$P = \frac{1}{R} e^{j(wt - kR - kD_1 \sin\theta \sin\Phi)} + \frac{A}{R} e^{j(wt - kR + kD_2 \sin\theta \sin\Phi - \varphi_2)}$$
$$+ \frac{B}{R} e^{j(wt - kR + kD_3 \sin\theta \cos\Phi - \varphi_3)}$$
$$+ \frac{C}{R} e^{j(wt - kR - kD_4 \sin\theta \cos\Phi - \varphi_4)}. \tag{2.35}$$

The directivity factor,

$$H(\theta,\Phi) = \frac{1}{(1+A+B+C)}\left| e^{-j(kD_1\sin\theta\sin\Phi)} + Ae^{j(kD_2\sin\theta\sin\Phi - \varphi_2)} + Be^{j(kD_3\sin\theta\cos\Phi - \varphi_3)} + Ce^{-j(kD_4\sin\theta\cos\Phi + \varphi_4)} \right|. \tag{2.36}$$

Expanding the complex terms yields

$$\begin{aligned} H(\theta,\Phi) = \frac{1}{(1+A+B+C)}\{&[\cos(kD_1\sin\theta\sin\Phi) + A\cos(kD_2\sin\theta\sin\Phi - \varphi_2) \\ &+ B\cos(kD_3\sin\theta\cos\Phi - \varphi_3) + C\cos(kD_4\sin\theta\cos\Phi + \varphi_4)]^2 \\ &+ [\sin(kD_1\sin\theta\sin\Phi) - A\sin(kD_2\sin\theta\sin\Phi - \varphi_2) \\ &- B\sin(kD_3\sin\theta\cos\Phi - \varphi_3) + C\sin(kD_4\sin\theta\cos\Phi + \varphi_4)]^2\}^{1/2}. \end{aligned} \tag{2.37}$$

This is the expression used for the computer program.

C. GRAPHICAL PRESENTATION OF THE DIRECTIVITY

1. Two-Dimensional Rectangular and Polar Plots

From equation (2.37), H (θ,Φ) versus θ, and H (θ,Φ) versus Φ can be plotted if either Φ or θ respectively is given constant value. In a rectangular plot, the directivity, F, which is equal to $20\log_{10}|H(\theta,\Phi)|$ is plotted on one axis and θ or Φ on the other. An example of this is seen in Figure 3.3. In a polar plot, the directional factor or beam pattern is a magnitude of the radial distance from the center of the plot while the appropriate angle is measured clockwise around the origin. An example of this is seen in Figure 3.4.

2. Three-Dimensional Cartesian Plot

From equation (2.37), H can be calculated and plotted as a function of both θ and Φ. This provides the three-dimensional surface with its elevation equal to $20\log_{10}|H(\theta,\Phi)|$ for each θ-Φ pair. An example of this is Figure 3.7. This form of presentation is difficult to interpret but can be a very useful analytical tool. Further explanations are given in the next chapter.

3. Contour Plot

A contour plot gives lines of constant H (θ,Φ). As an example, let $kD_1 = kD_2 = kD_3 = kD_4 = kD$, $\varphi_2 = 0$, $\varphi_3 = \varphi_4 = \pi$ and $A = B = C = 1$. Equation (2.37) then can be simplified to

$$H(\theta,\Phi) = \frac{1}{2}\,|\cos(kD\sin\theta\sin\Phi) - \cos(kD\sin\theta\cos\Phi)|. \tag{2.38}$$

By setting $H(\theta,\Phi) = Q$, the desired value, and $\sin\theta\sin\Phi = c_1$, and $\sin\theta\cos\Phi = c_2$ where $|c_1| \neq |c_2|$, we get

$$|\cos(kDc_1) - \cos(kDc_2)| = 2Q. \tag{2.39}$$

This transcendental equation is then solved for c_1 and c_2. Now, with c_1 and c_2 determined, we need to solve the second transcendental equation

$$\tan\Phi = \frac{c_1}{c_2}\ . \tag{2.40}$$

which was derived by dividing c_1 by c_2, for Φ and then, for θ using the θ-Φ relationship. However, many of c_1-c_2 pairs are possible solutions to the first transcendental equation. Therefore, equation (2.40) must be solved for all the different c_1-c_2 pairs by repeating the above procedure. This would result in a contour plot such as Figure 3.10. This analytical approach was not pursued further in this research because other algorithms for extracting constant values of F for varying θ and Φ had already been obtained and successfully applied. However, the utility of the above transcendental equation approach may well bear further investigation, and we will pursue a little case-by-case analysis for some cases for which the solution of equations (2.39) and (2.40) is relatively straightforward.

III. PROGRAM DEVELOPMENT

In analyzing the directional and frequency properties of shaded and phased simple arrays several types of display methods were needed. At the first stage of developing the computer program, a HEWLETT-PACKARD 86B computer and a HP7090A MEASUREMENT PLOTTING SYSTEM were used. By using this equipment we were able to get two-dimensional plots as shown in Figures 3.1 and 3.2. However, it took much time in executing the program and also we could not do three-dimensional plottings.

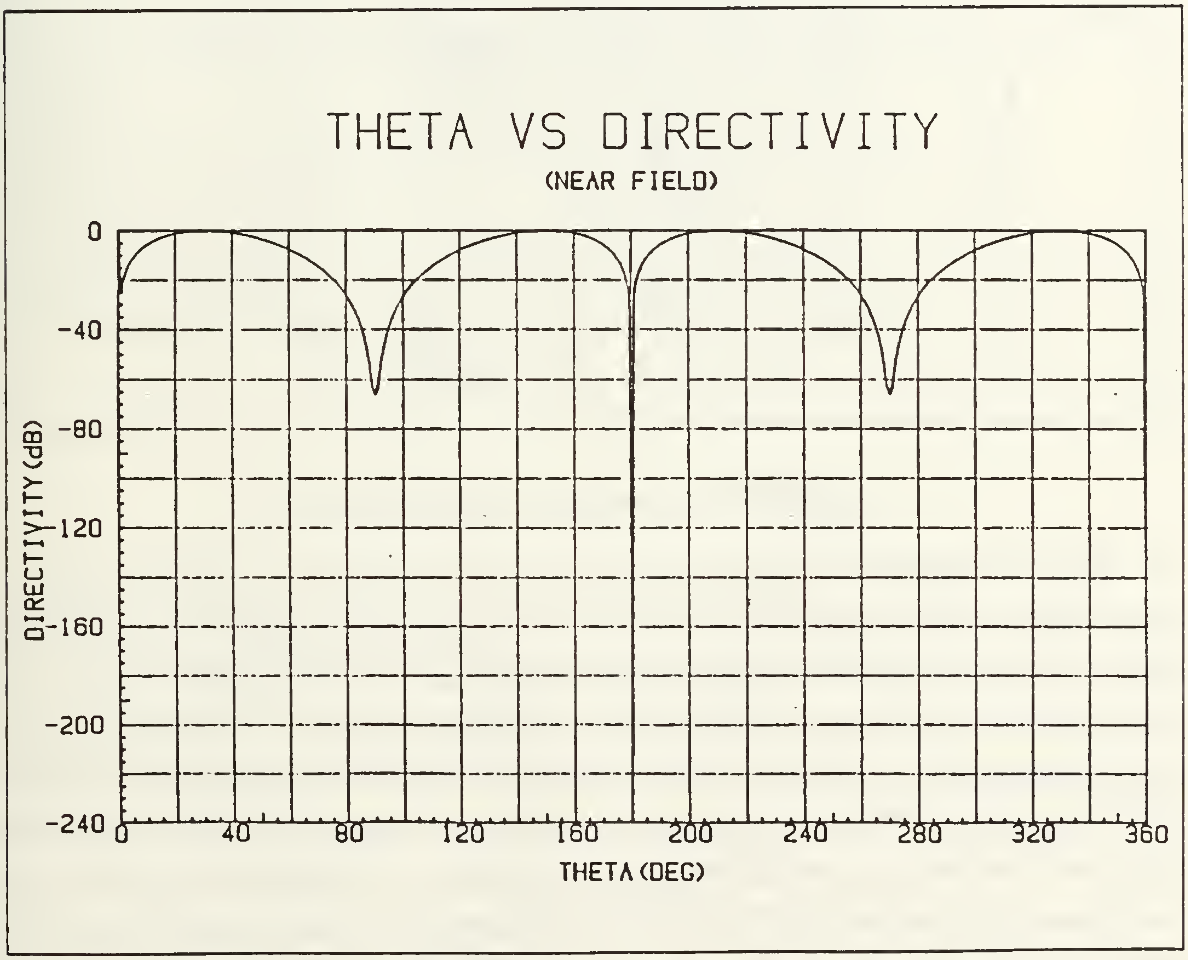

Figure 3.1 2-D rectangular plot (HP 86B).

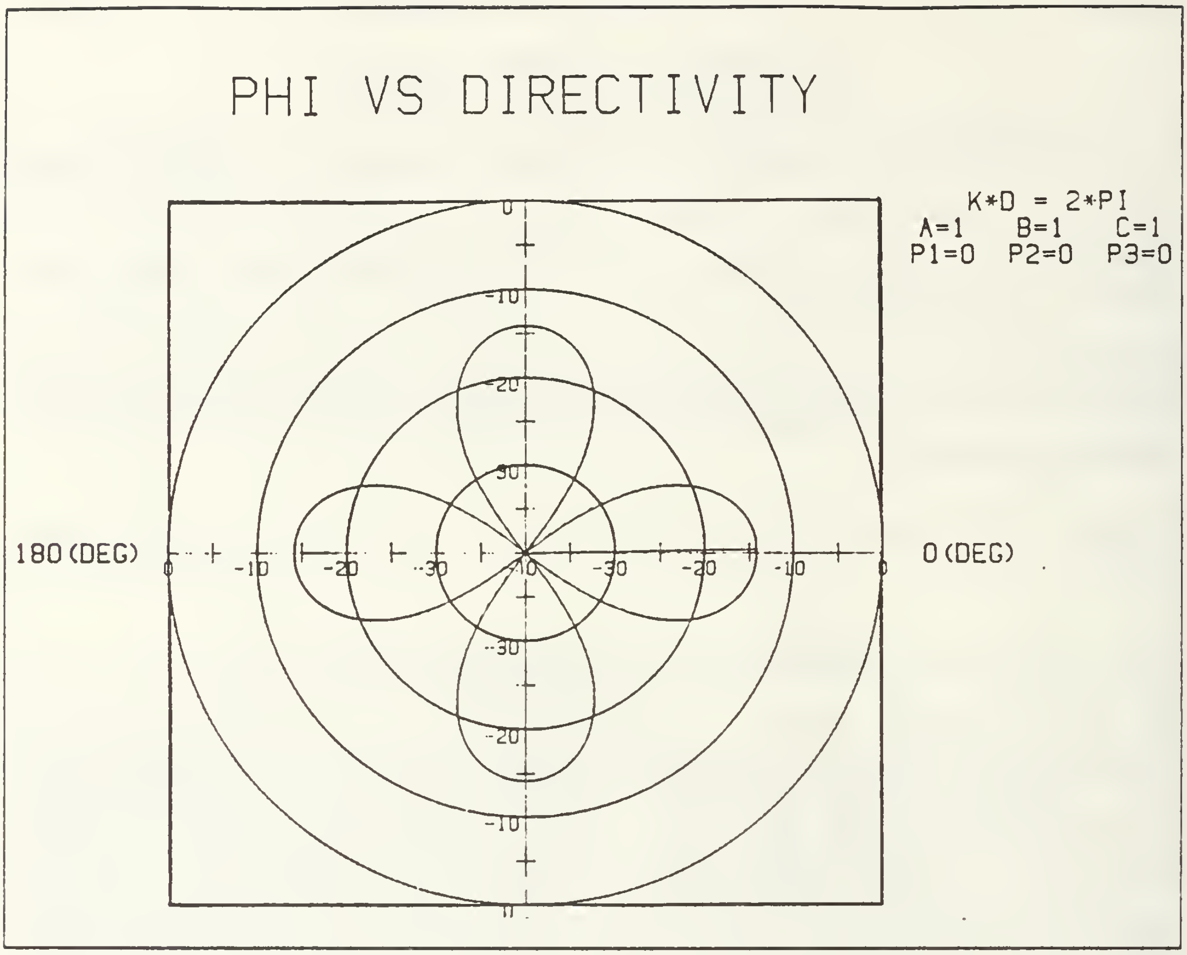

Figure 3.2 2-D circular plot (HP 86B).

To get a complete understanding of the beam pattern, three-dimensional displays viewed from various angles were essential. Consequently, alternative methods of display were programmed in FORTRAN and executed on the IBM 3033. There are several reasons why this proved to be the most desirable method. Primarily, a three-dimensional graphics software package (DISSPLA) is available for use on the IBM 3033. Secondly, FORTRAN generated the numerical output with greatly increased efficiency when using the EXTENDED FORTRAN COMPILER [Ref. 8: p.18]. Finally, the IBM 3033 has many more output devices such as VERSTEC, TEK618 and SHERPA to name a few. Therefore, the programs used in the HEWLETT-PACKARD 86B were rewritten in FORTRAN. The translation from BASIC to FORTRAN required some changes in variable names along with the use of some convenient function calls. For reference, some of the original BASIC programs are attached in Appendix A.

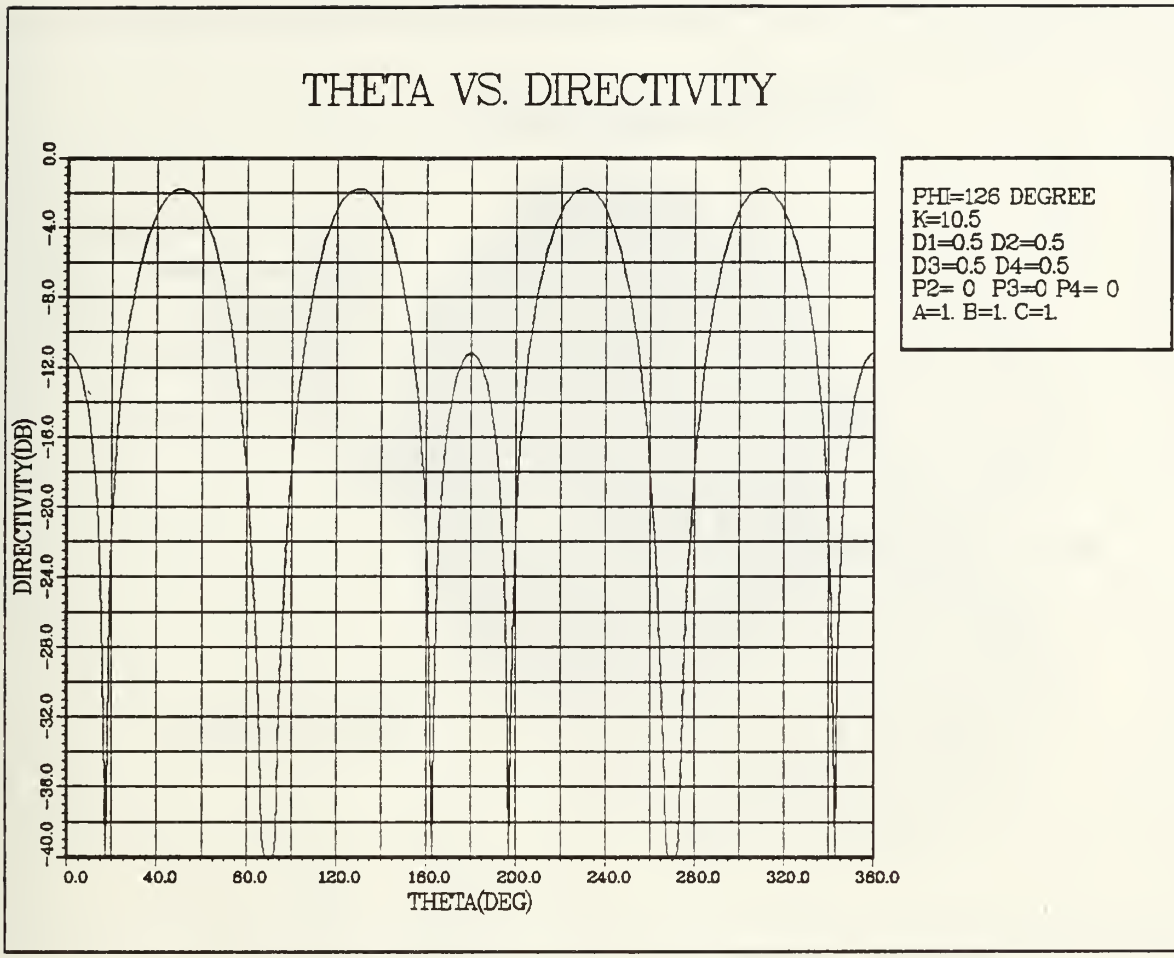

Figure 3.3 2-D rectangular plot (DISSPLA).

In the trial of analyzing only with numerical outputs, BASIC had become ineffective in recognizing details due to the very large number of computed values. At this stage the graphic package DISSPLA, available on the IBM 3033 computer, was used in conjunction with these programs. The DISSPLA package is a library of FORTRAN subroutines that facilitate data plotting. It is also device independent, which means that it does not rely upon features particular to any type of graphical device and has its own extensive symbol and character generation routines. By being device independent, programs of the HEWLETT-PACKARD 86B could be translated without difficulty. Therefore, DISSPLA was used to produce both two-dimensional and three-dimensional graphs. The data used to compute graphs could be generated within the FORTRAN program or read from a data file. The former method was used here because data files took a great amount of file space due to the large volume of values.

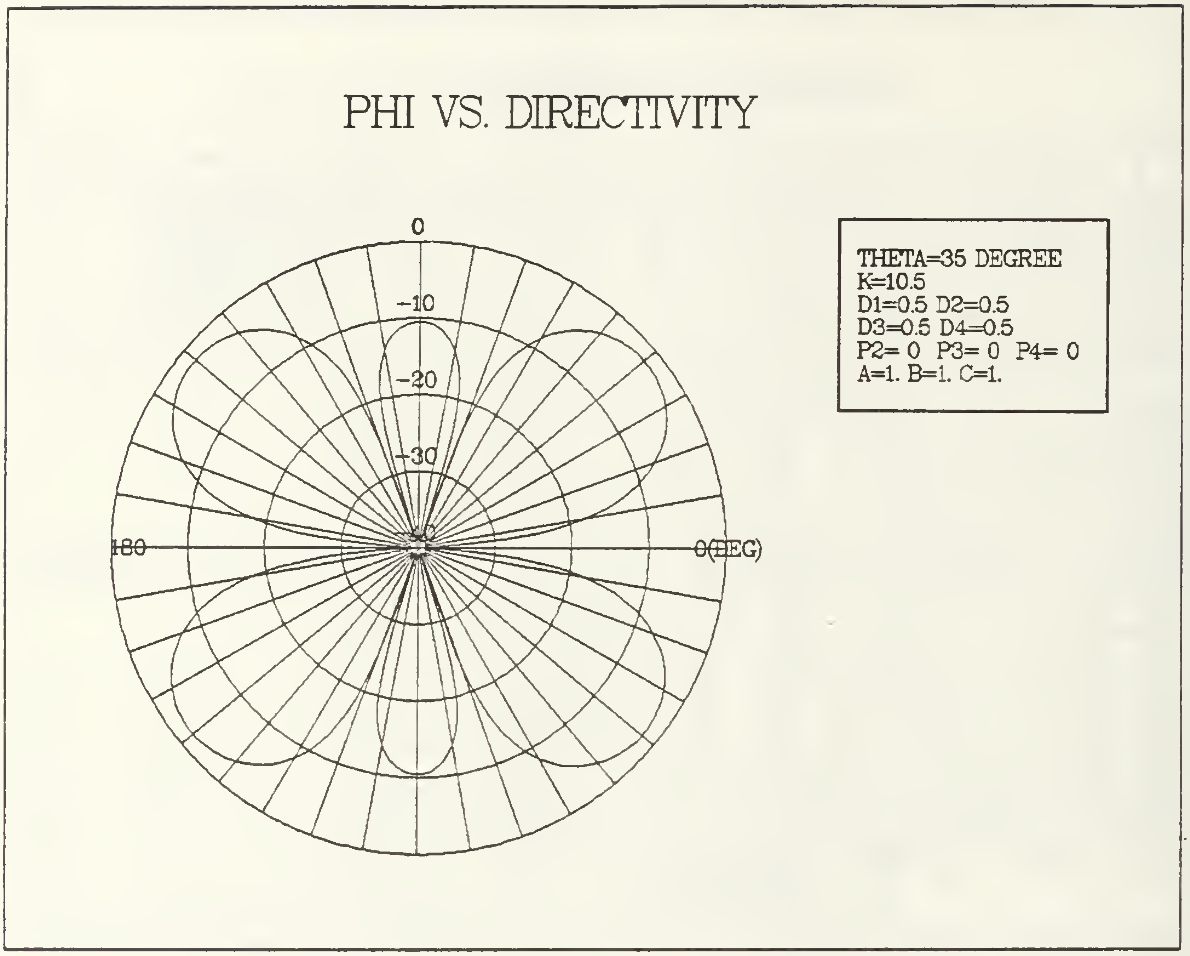

Figure 3.4 2-D circular plot (DISSPLA).

Two-dimensional graphs were initially tried. By holding one parameter constant and with the use of some array variables, plots of directivity versus angle were obtained. Examples of two kinds of displays are shown in Figures 3.3 and 3.4. Programs are attached in Appendix B.

To predict the real shape of a directivity pattern in three-dimensions, three-dimensional graphics had to be developed. In trying to get some satisfying three-dimensional plotting, all methods in DISSPLA were tried. They are SURFUN, and SURMAT for regular matrix, scattered points, and three-dimensional vector drawing.

SURFUN is a subroutine that draws the surface from points in the z direction in conjunction with a grid in the x-y plane on the condition that z=f(x,y) is given. One constraint that was faced in applying this function was that there was more than one z value for a specific x-y coordinate.

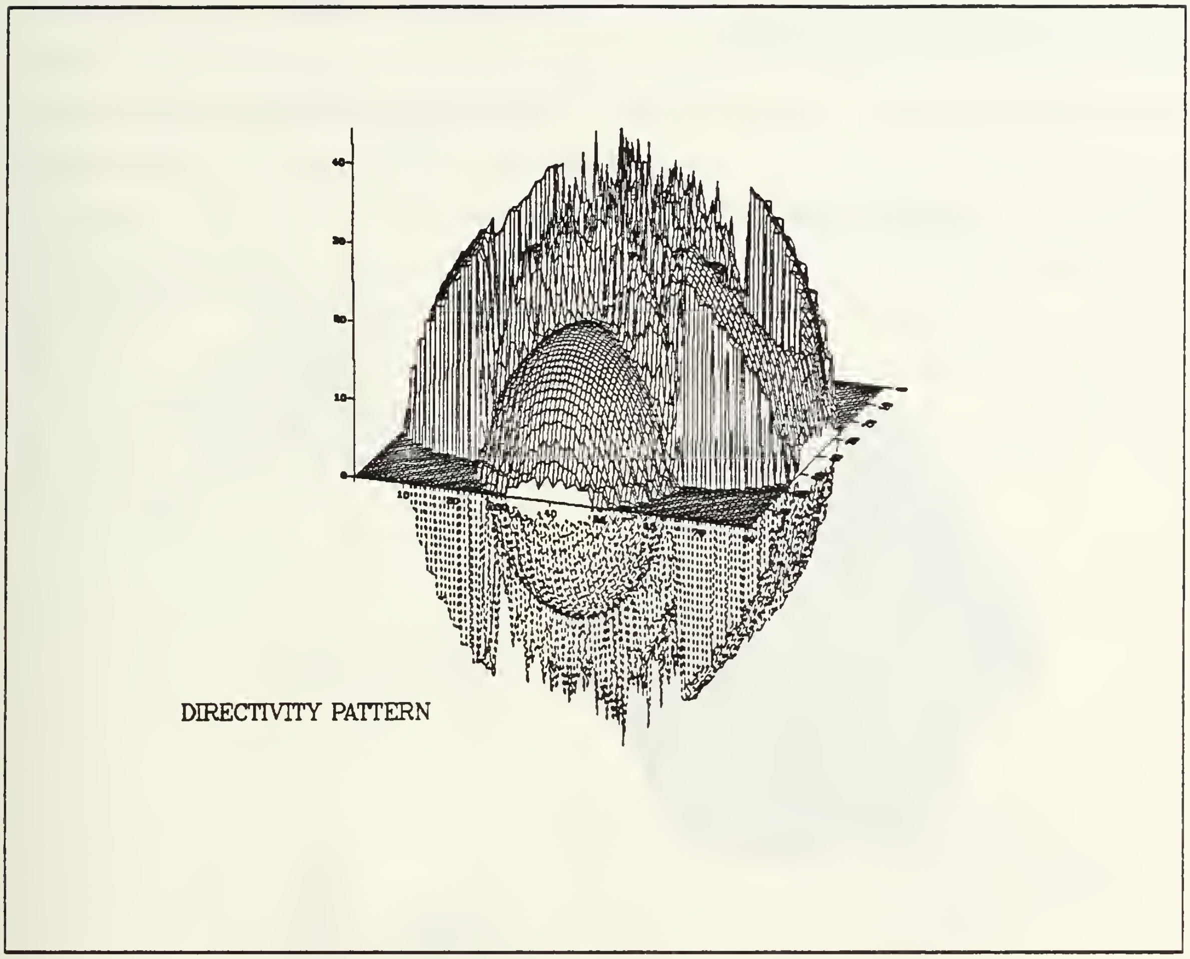

Figure 3.5   3-D plot(SURMAT for scattered points).

The next trial was SURMAT for a regular matrix (for example, a rectangular three-dimensional lattice of points). For the same reason as in applying the SURFUN subroutine, this also turned out to be non-applicable even though all data points were translated into a regular matrix.

The next option tried was SURMAT for scattered points (for example, a three-dimensional irregular cluster of points). As seen in Figure 3.5 it also was unsuccessful due to more than one point on one specific coordinate of the x-y plane. The program is listed in Appendix C for reference.

The last option, the three-dimensional vector drawing method gave us a more understandable display as shown in Figure 3.6. However, it did not show the beam pattern clearly because all the lines were visible, even from different view angles. At this stage the problem was the removal of hidden lines. Unfortunately, that was not

possible because the starting and ending points of the hidden lines could not found. The program is listed in Appendix D.

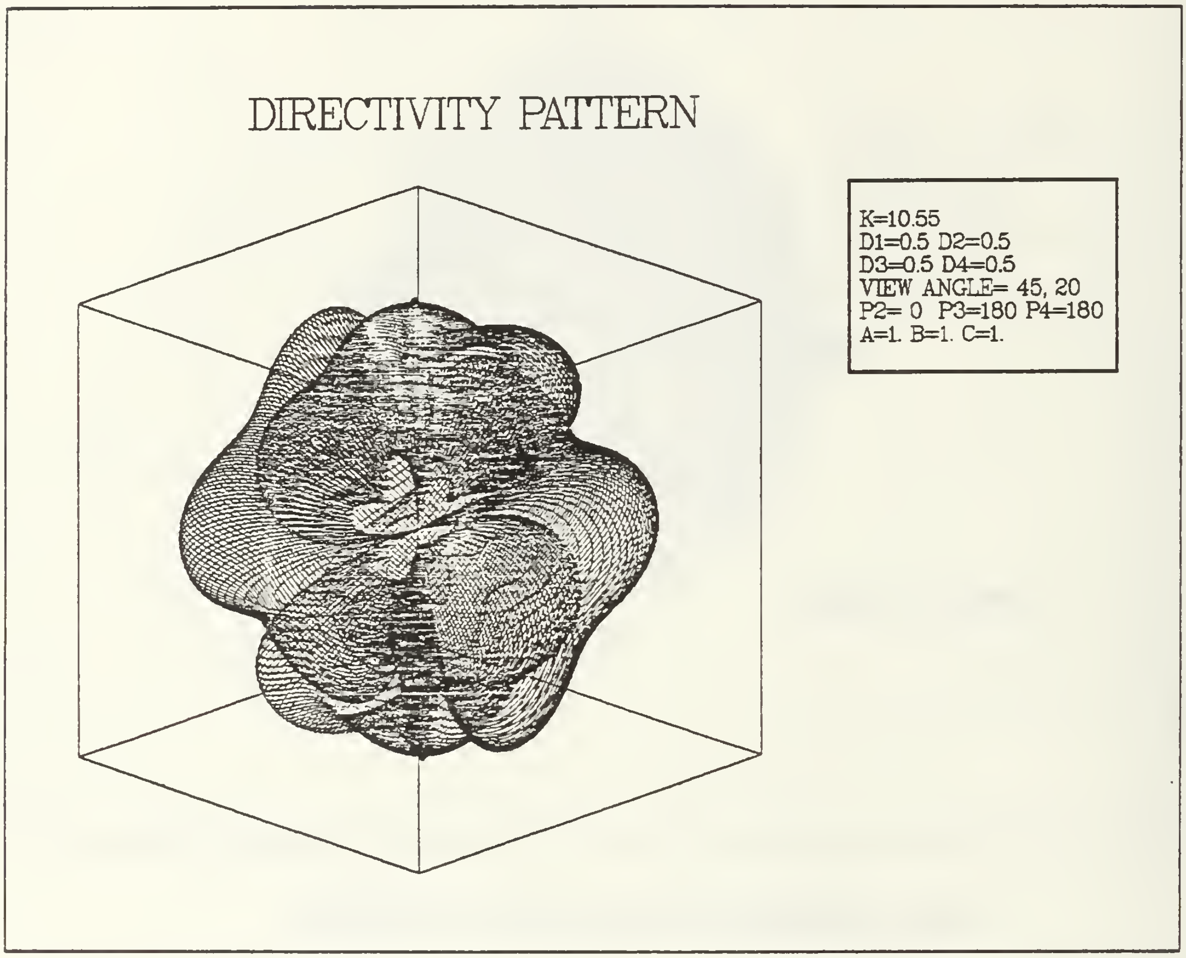

Figure 3.6 3-D plot(vector drawing method).

Consequently, with the consideration of all the constraints mentioned above, another type of format was made to see the details of the beam pattern. Now, a plot was made using the function SURMAT about the θ-Φ plane instead of the x-y plane. This eliminated the previous multiple value problem. The results showed the most desirable presentation among all those tried. As shown in Figure 3.7 it gives a clearer appreciation of the directivity pattern in conjunction with θ and Φ. The program is listed in Appendix E.

We can relate this three-dimensional graph (Figure 3.7) to the two-dimensional graphs (Figures 3.3 and 3.4) for interpretation. As shown in Figure 3.3 the x-axis is

the angle and the y-axis is the directivity which is expressed in dB. Figure 3.4 is the circular graph with angle working counterclockwise in 10° increments and each circle is an increment of 10 dB with the center of - 40 dB. Figure 3.7 is the three-dimensional graph from the view point of 20° from the x-z plane, and 60° from the x-y plane. Here, the x-axis is Φ, the y-axis is θ and the z-axis is the beam pattern (dB). From Figure 3.3 four major points can be found at approximately 50°, 130°, 230° and 310° of θ with Φ fixed at 126°. From Figure 3.7 the same feature can be determined at 50° of θ, 126° of Φ as seen in Figure 3.3. Since Figure 3.3 was made by holding Φ constant at 126°, one can look along the Φ = 126° line in Figure 3.7 and note the null at θ = 90°, the maximum at θ = 50°, and the relative maximum at θ = 0°. Note the heavy lines in Figure 3.7.

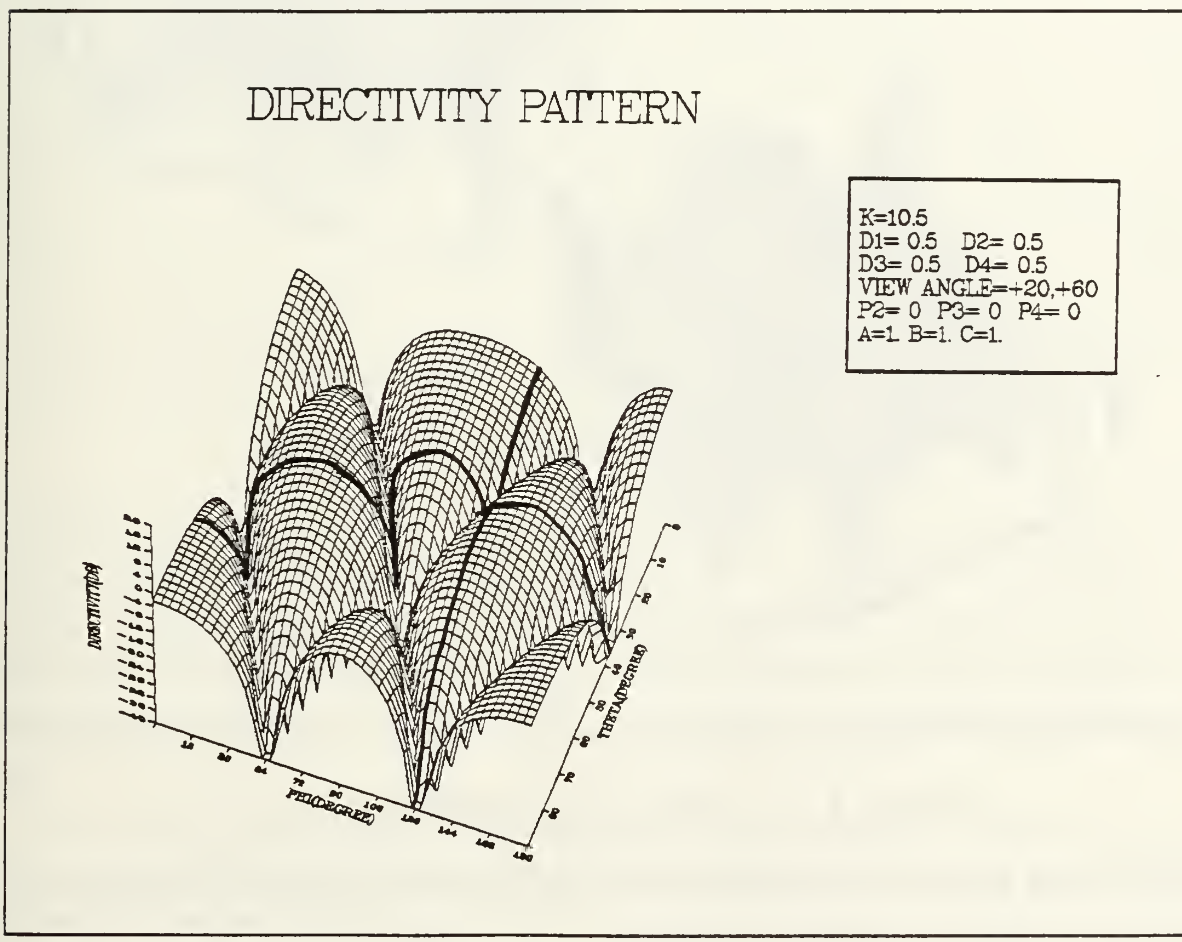

Figure 3.7 3-D plot(SURMAT in θ-Φ plane).

From the circular graph (Figure 3.4) four major points can be found approximatly at 40°, 140°, 220° and 320° of Φ with θ fixed at 35°. In the three-dimensional graph one of these major points is seen approximately at 35° of θ, 40° of Φ and the other major point is seen approximately at 35° of θ, 140° of Φ. Comparison is made easier when we see Figure 3.8 and Figure 3.9 which were drawn with the surfaces cut at Φ = 126° and θ = 35° respectively. Note the shift in axes between the two figures. All these points of two-dimensional graphs correspond to those of the three-dimensional graph.

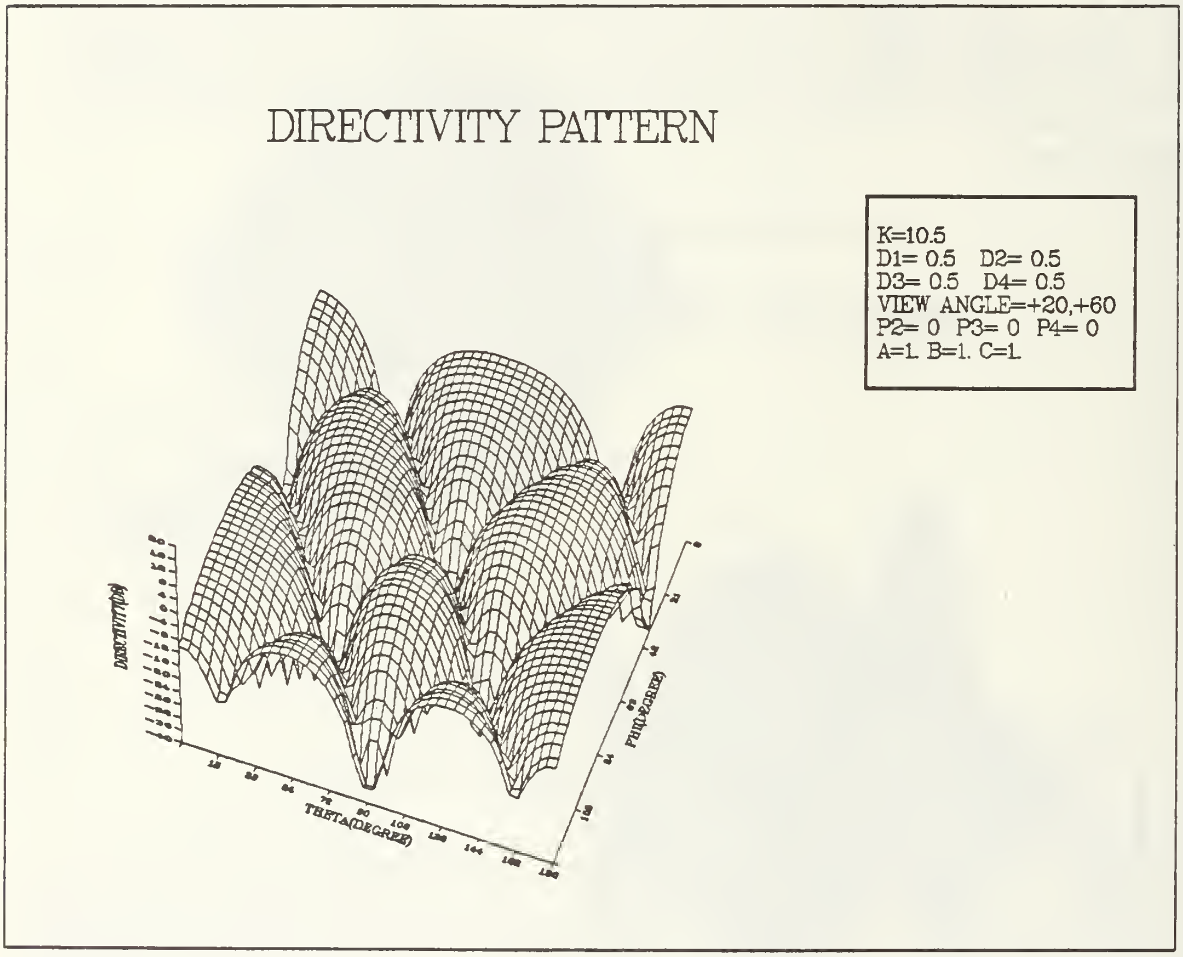

Figure 3.8 3-D plot(SURMAT in θ-Φ plane).

Inversely, every point of the three-dimensional graph can be read in two-dimensional graphs to see detailed values whenever needed.

Finally, a trial was made to draw a constant value plot of the beam pattern. The first approach was to derive the functions of $\Phi = f(\theta)$ or $\theta = f(\Phi)$ and plot these on

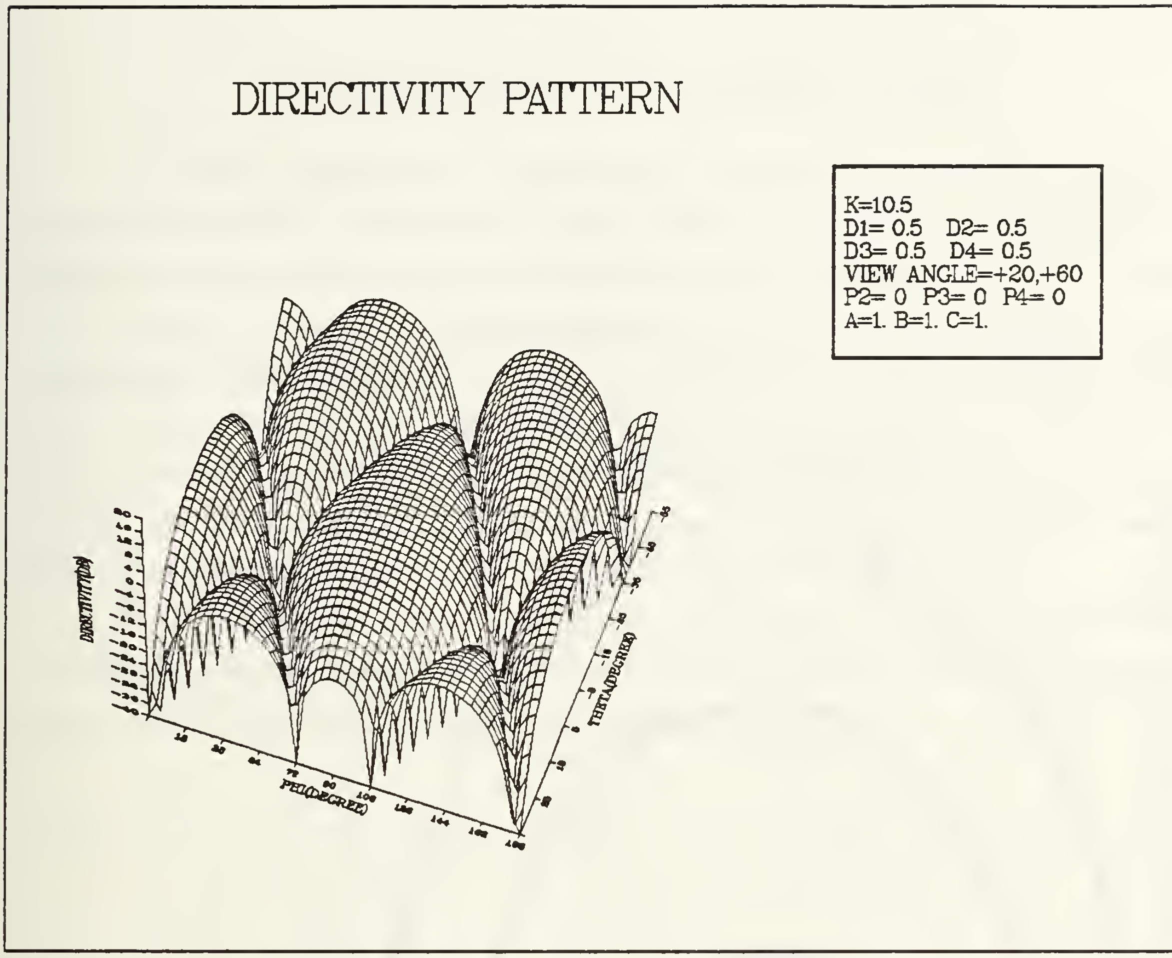

Figure 3.9 3-D plot(SURMAT in θ-Φ plane).

the θ-Φ plane. However, failing to derive these relationships for the general four element case made this method of making a contour plot of a fixed F value impossible. Instead, a modified version of the existing θ-Φ program was used. It sorted on a small range of values about the desired value of F to find the corresponding θ-Φ coordinates which were then plotted as in Figure 3.10. This type of plot is included throughout the study.

With these forms of display and the speed of the FORTRAN version of this program we can now use this method to study the directional and frequency properties of shaded and phased simple arrays.

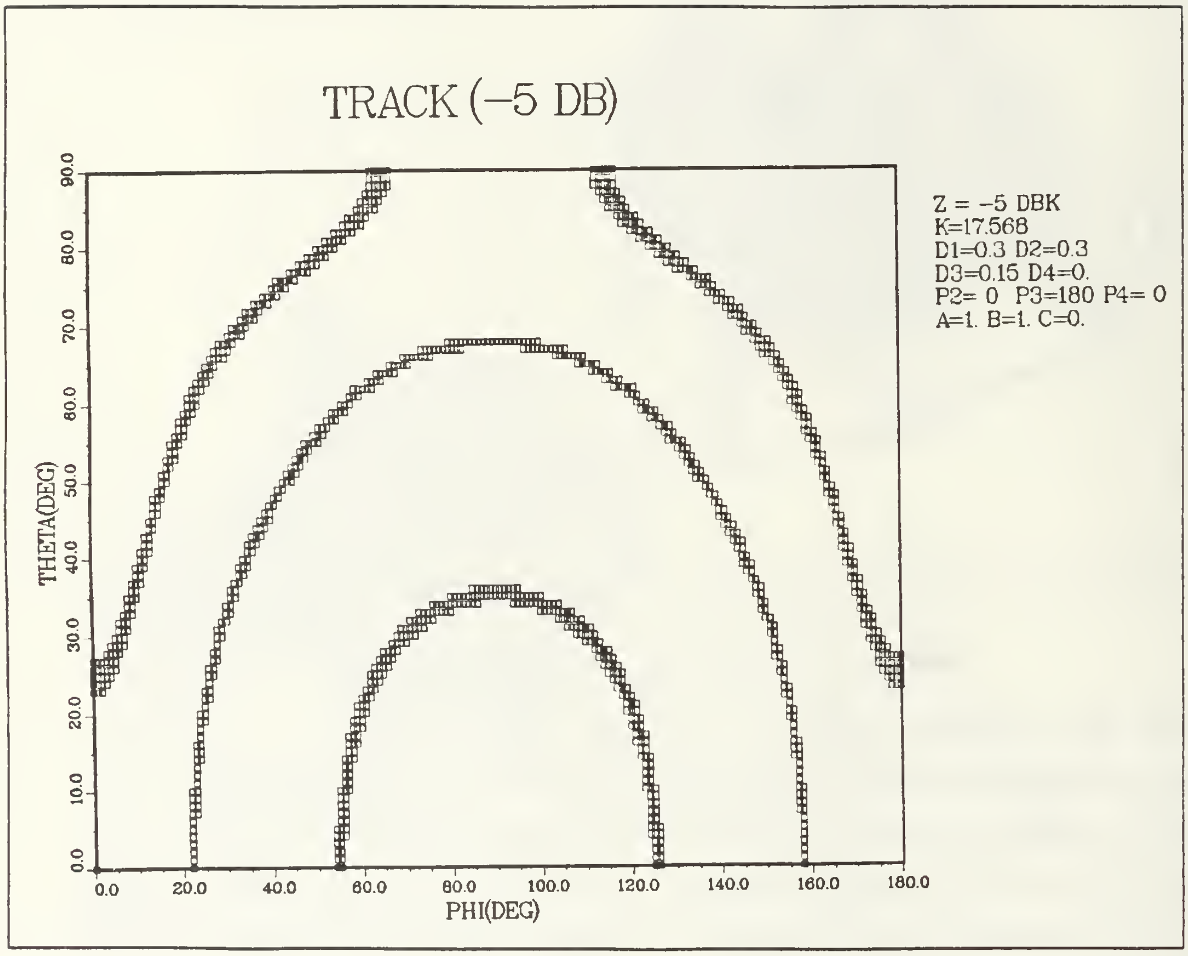

Figure 3.10 contour plot (TRACK).

IV. COMPARISON WITH SAMPLE CASES

In making comparisons, some simple parameters were used to make the comparisons easier. There are three cases included in this chapter. Each case has a unique set of input data, and computer generated and experimental plots. In all cases, a two points were picked and hand calculations made to verify the computer output. An example of the hand calculations is given for the first case only. Comparisons were also made between hand or computer generated values and the two-dimensional polar plot, between the theoretical two-dimensional plot and the experimental data plot, between the two-dimensional plot and the three-dimensional plot, and finally between a fixed value of the beam pattern (a "track") and its three-dimensional plot.

While in general, $\theta(\Phi)$ or $\Phi(\theta)$ for a constant F could not be obtained analytically, in a few cases, included below, it was possible to obtain the functional dependencies. These are discussed in the following cases.

A. CASE 1

When $kD_1 = kD_2 = kD_3 = kD_4 = 5.275$,

$\varphi_2 = 0, \varphi_3 = \varphi_4 = \pi$,

$A = B = C = 1$

equation (2.37) can be simplified as

$$H(\theta,\Phi) = \frac{1}{2} |\cos(5.275 \sin\theta\sin\Phi) - \cos(5.275 \sin\theta\cos\Phi)|. \tag{4.1}$$

Using the above input data with values of $\theta = 40°$ and $\Phi = 0°$ we get $H(\theta,\Phi) = 0.984566$ and $F(\theta,\Phi) = -0.135104$ from the computer output as seen in Appendix G. If we use the above simplified equation and hand-computation, we get $H(\theta,\Phi) = 0.98457$ and $F(\theta,\Phi) = -0.135068$.

In the same way, if $\theta = 90°$ and $\Phi = 0°$ then we get $H = 0.233302$, and $F = -12.641622$ from the computer output and $H = 0.23330$, and $F = -12.6417$ from the hand-calculation. These hand-calculated values are almost the same the the computer output. Comparisons can also be made between these selected values and the two-dimensional plot, Figure 4.1a. Additionally, the above two-dimensional plot

corresponds well in shape with Figure 4.1b which is from LCDR John Butler's experiment [Ref. 10].

If we compare the shape of the two-dimensional plot (Figure 4.1a) with that of the three-dimensional plot, Figure 4.1c, we see that beam pattern of the two-dimensional graph is identical in the $\Phi = 0°$ plane of the three-dimensional plot.

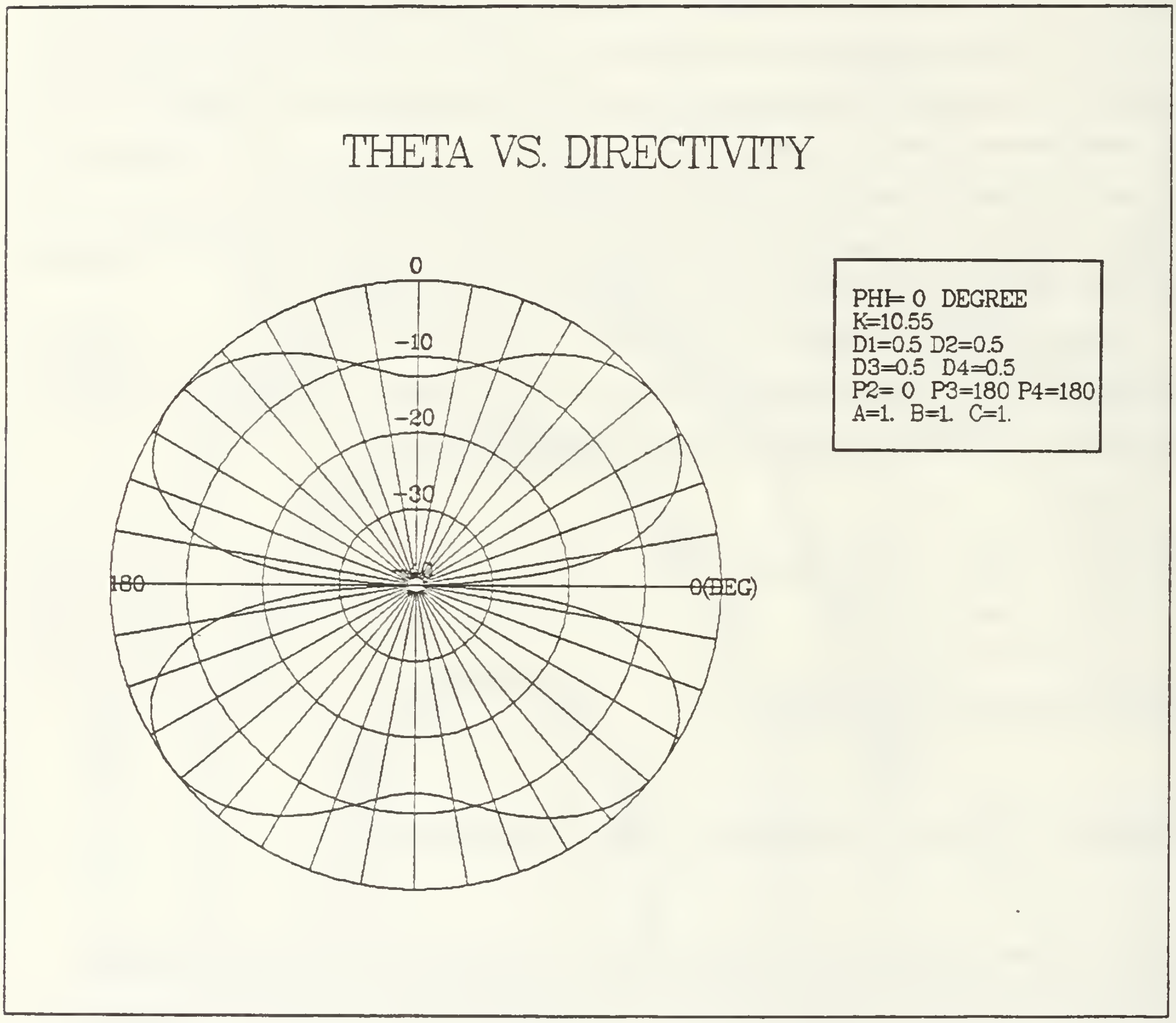

Figure 4.1a 2-D plot from the computer output.

A two-dimensional plot of equation (4.1), of F values between -10.9 dB and -10.0 dB results in Figure 4.1d. For F values less than -90.0 dB we get Figure 4.1e. In the case where F < -90 dB, H < $10^{-90/20}$ which is small enough to be assumed to be 0, $|c_1| \sim |c_2|$ or $\theta = n\pi$ n = 0,1,2---, and equation (2.40) can be $\tan\Phi = 1$ or -1. From these resulting equations we can extract $\Phi = 45° + n\pi/2$, n = 1,2 ---. As seen

in Figure 4.1e, when F < -90 dB the asymptote matches the nulls in the θ-Φ relationship of Figure 4.1c. Note the nulls at $\theta = 0°, 180°$ for all Φ, and $\Phi = 45°$. These figures of constant dB level aid in the interpretation of Figure 4.1c. The modified P3D program (TRACE) is included in Appendix F.

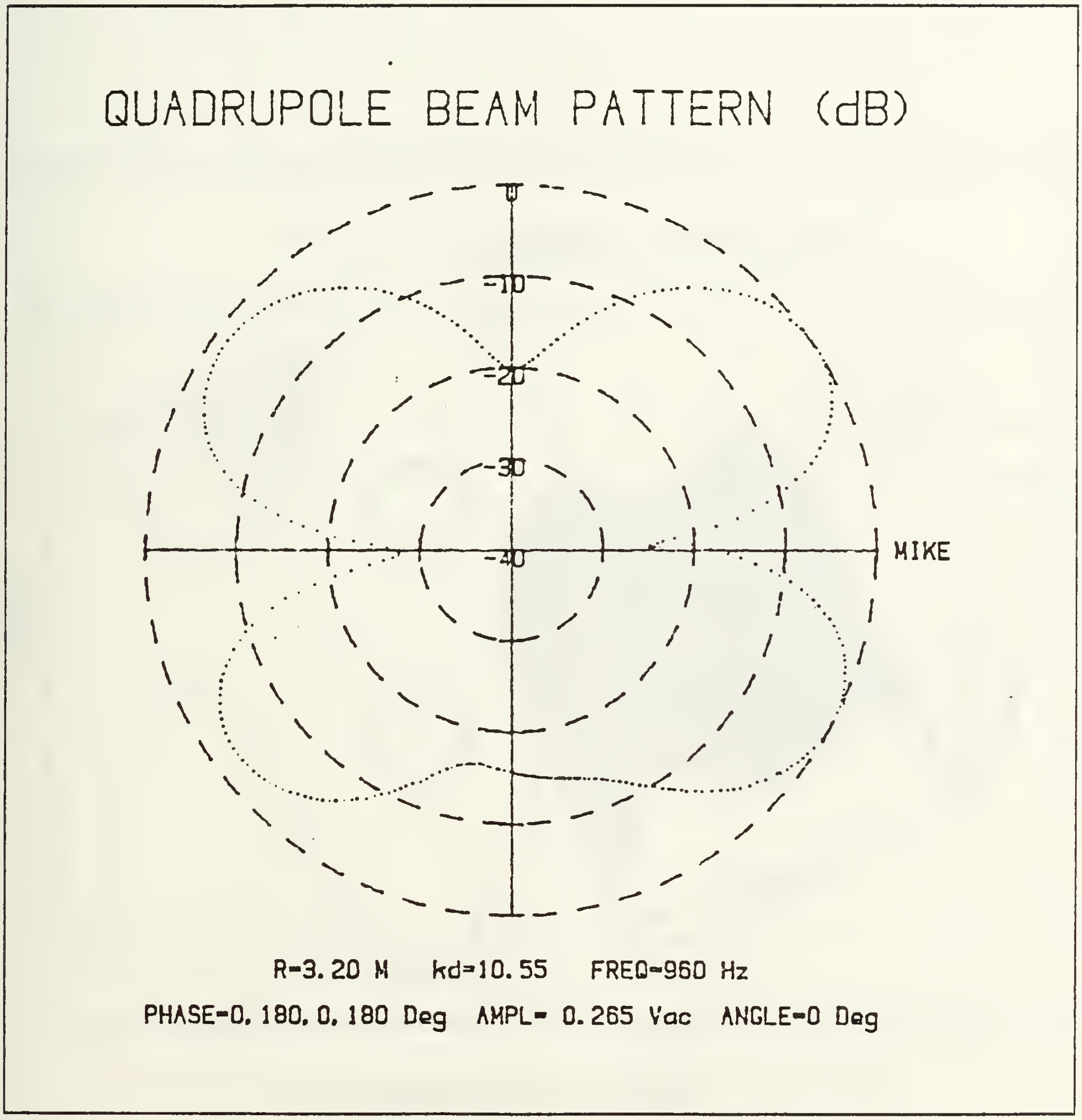

Figure 4.1b 2-D plot from the experiment.

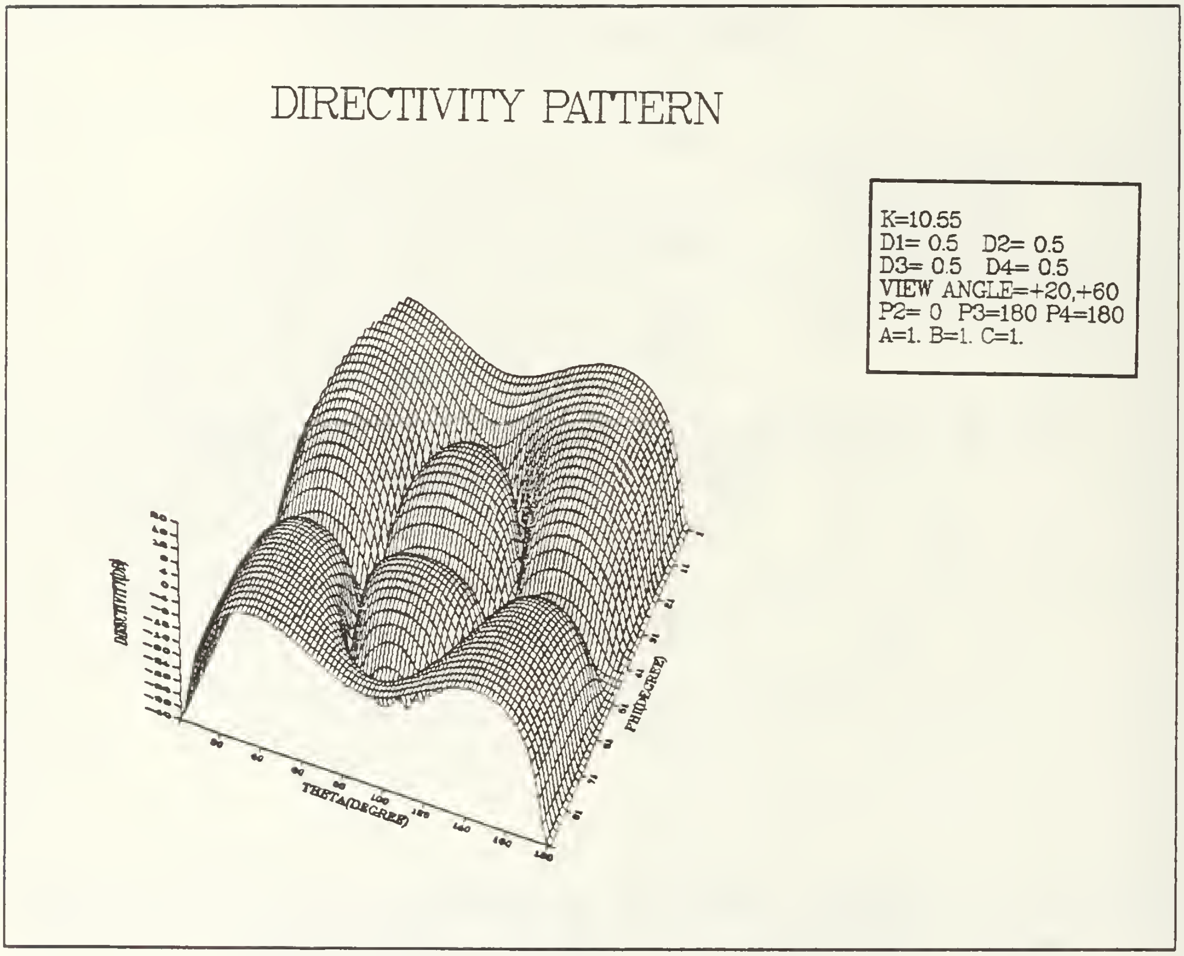

Figure 4.1c 3-D plot from the computer output.

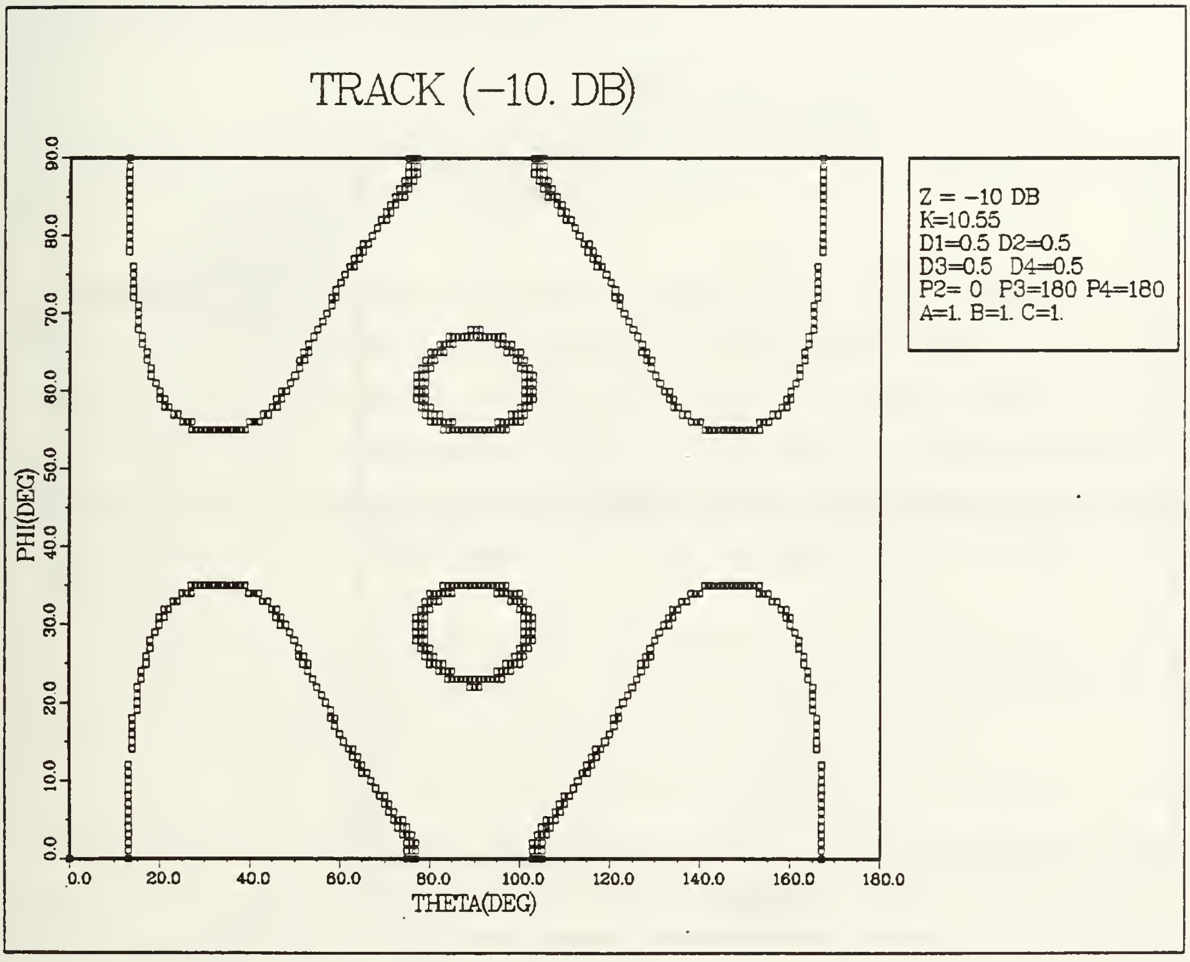

Figure 4.1d Track (-10 dB).

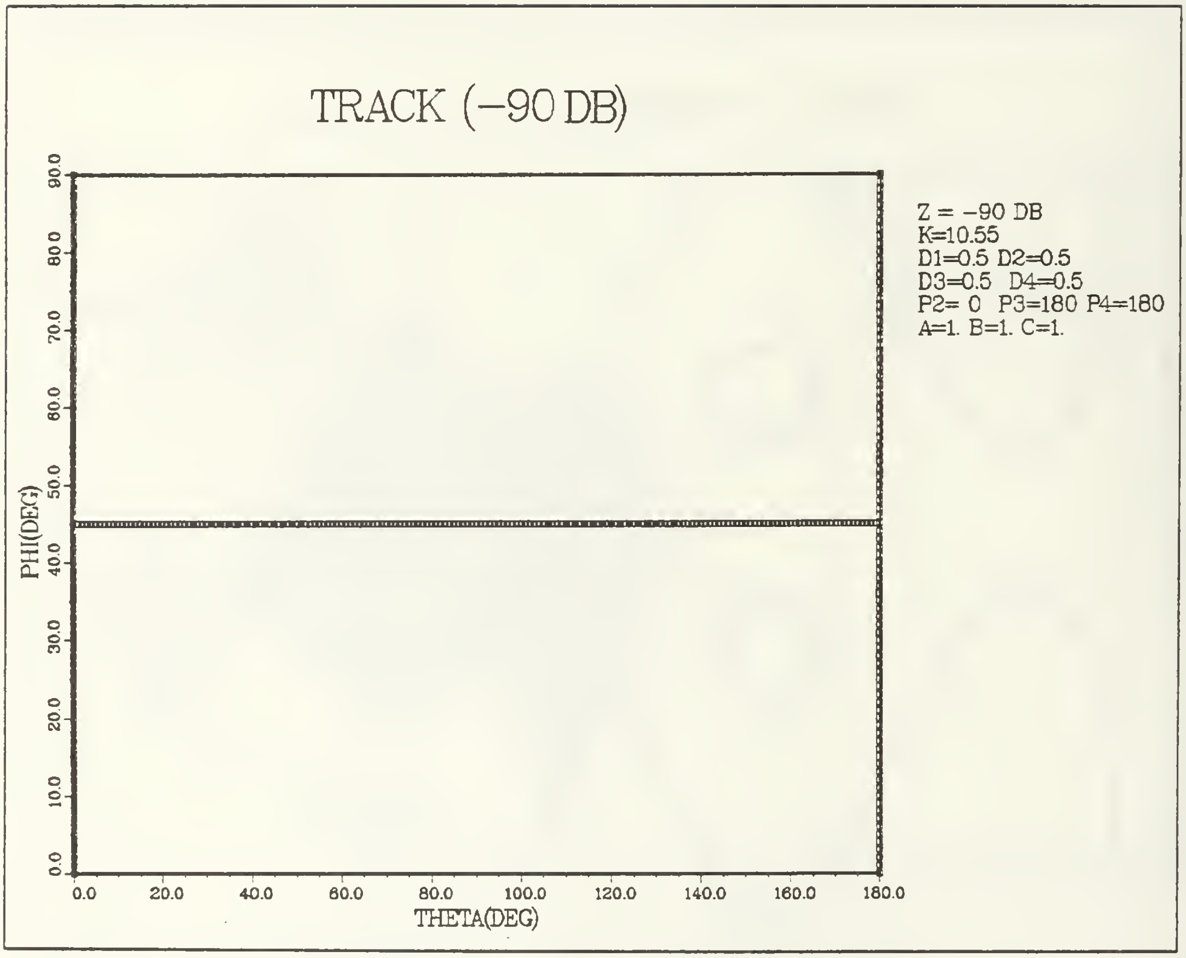

Figure 4.1e Track (-90 dB).

B. CASE 2

In this case, a triplet array is investigated. Referring to Figure 2.3, the fourth element is turned off and its opposing element is moved toward the center of the array so its distances is half that of the two elements. Also, the source 2 is 180° out of phase with the other two elements.

When $kD_1 = kD_2 = 5.2758$,

$kD_3 = 2.6379$, $kD_4 = 0$,

$\varphi_2 = \pi$, $\varphi_3 = \varphi_4 = 0$,

$A = B = 1, C = 0$

the equation (2.37) can be simplified as

$$H(\theta,\Phi) = \frac{1}{3}\{[\cos(2.6379 \sin\theta\cos\Phi)]^2 + [2\sin(5.2758 \sin\theta\sin\Phi) - \sin(2.6379 \sin\theta\cos\Phi)]^2\}^{1/2}. \quad (4.2)$$

If values are calculated from the equation (4.2) as in case 1, then comparisons can be made between these calculated values and the two-dimensional plot as seen in Figure 4.2a (for $\theta = 0°$, $20°$ and $90°$, and $\Phi = 90°$, we get $F = -9.5424$, -2.7431 and -3.6776 respectively from hand-computation.). Additionally, the two-dimensional plot corresponds well in shape with Figure 4.2b from the experiment (Ignore the ordering of the relative phases in this figures; it is the consequence of a different labeling convention).

If we compare the shape of a two-dimensional plot (Figure 4.2a) with that of the three-dimensional plot (Figure 4.2c), we see that beam pattern of the two-dimensional graph is identical in the $\Phi = 90°$ plane of the three-dimensional plot.

For a contour plot of this case, a two-dimensioal plot of equation (4.2) of F values between -5.9 dB and -5.0 dB results Figure 4.2d. For F values between -10.9 dB and -10.0 dB, we get Figure 4.2e. For F values less than -35.0 dB, we get Figure 4.2f. From equation (4.2), we get $F = -35.876$ for $\theta = 143°$ and $\Phi = 10°$ from hand-calculation. This point is seen in Figure 4.2f. Successive examination of Figure 4.2d through 4.2f shows how the contour lines migrate as lower and lower values of F are examined. These figures of constant dB level aid in the interpretation of Figure 4.2c. The modified P3D program (TRACE) is included in Appendix F.

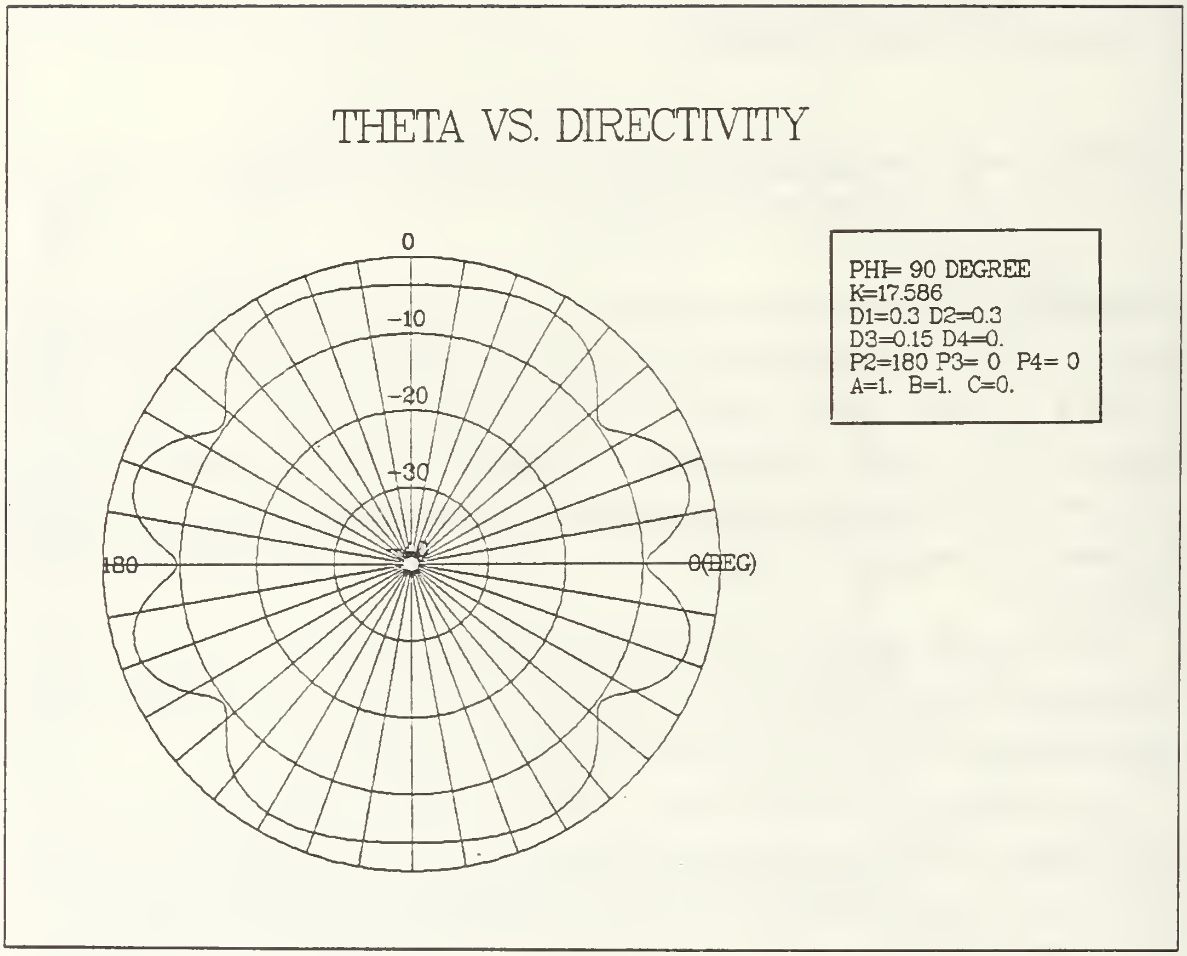

Figure 4.2a 2-D plot from the computer output.

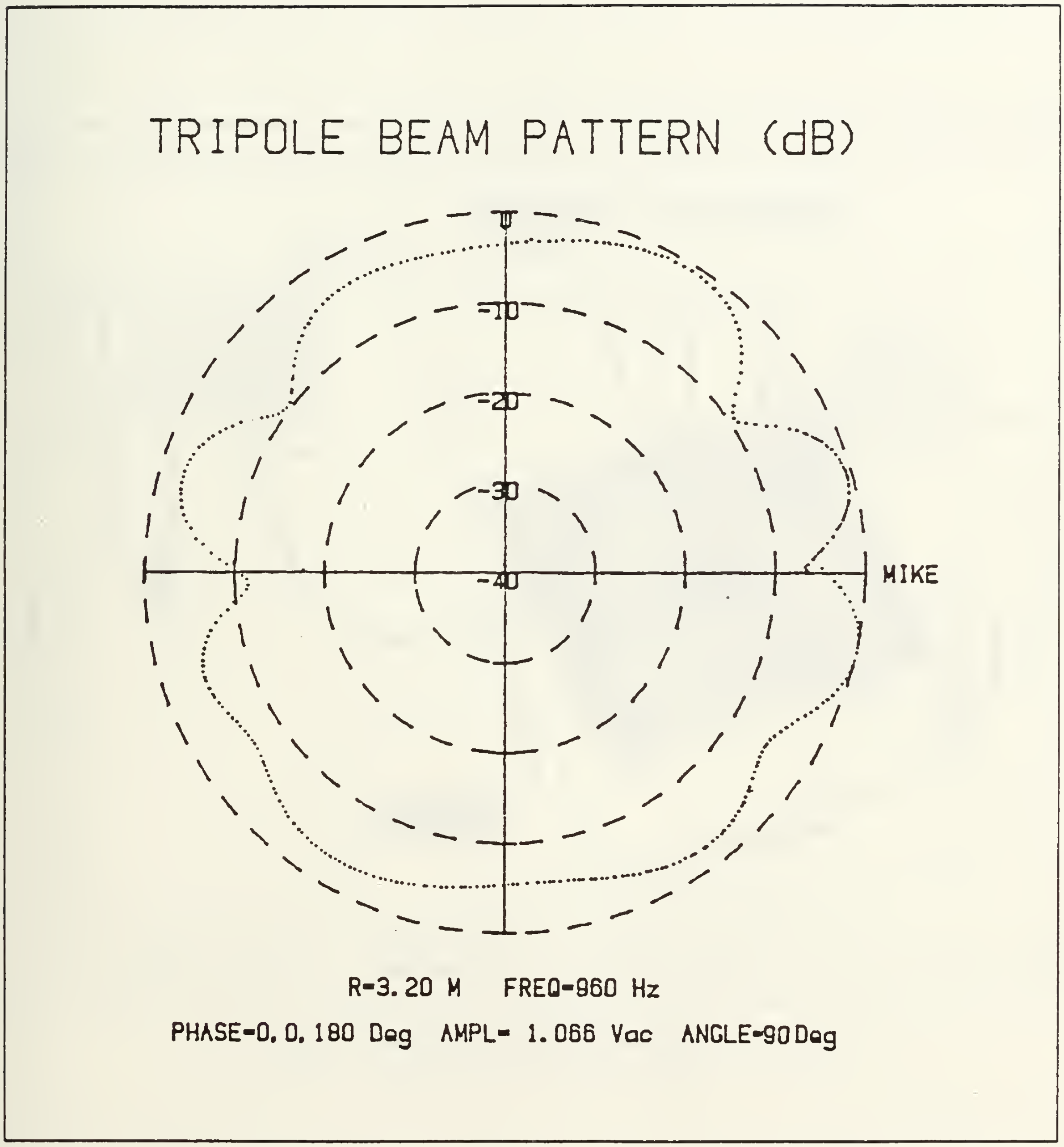

Figure 4.2b 2-D plot from the experiment.

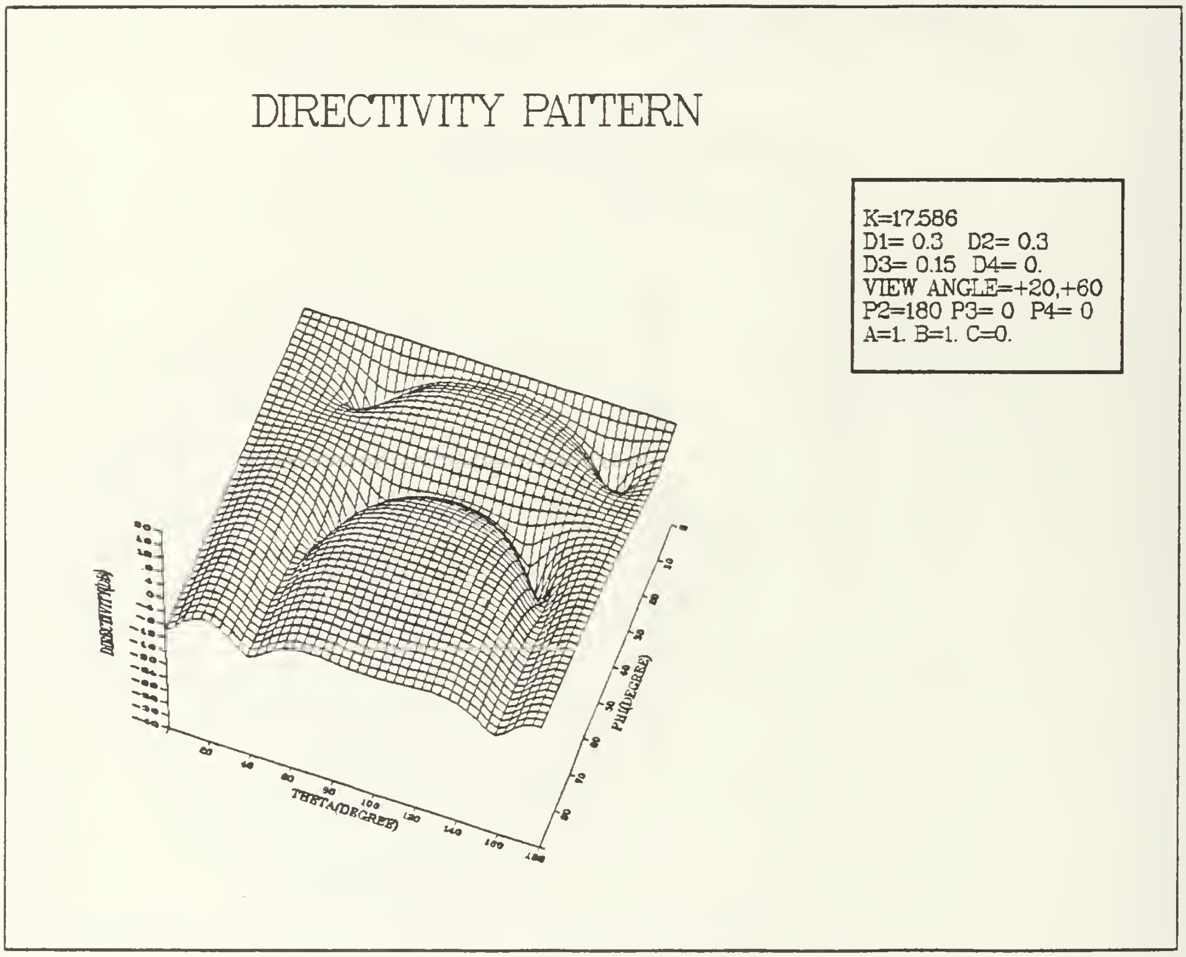

Figure 4.2c 3-D plot from the computer output.

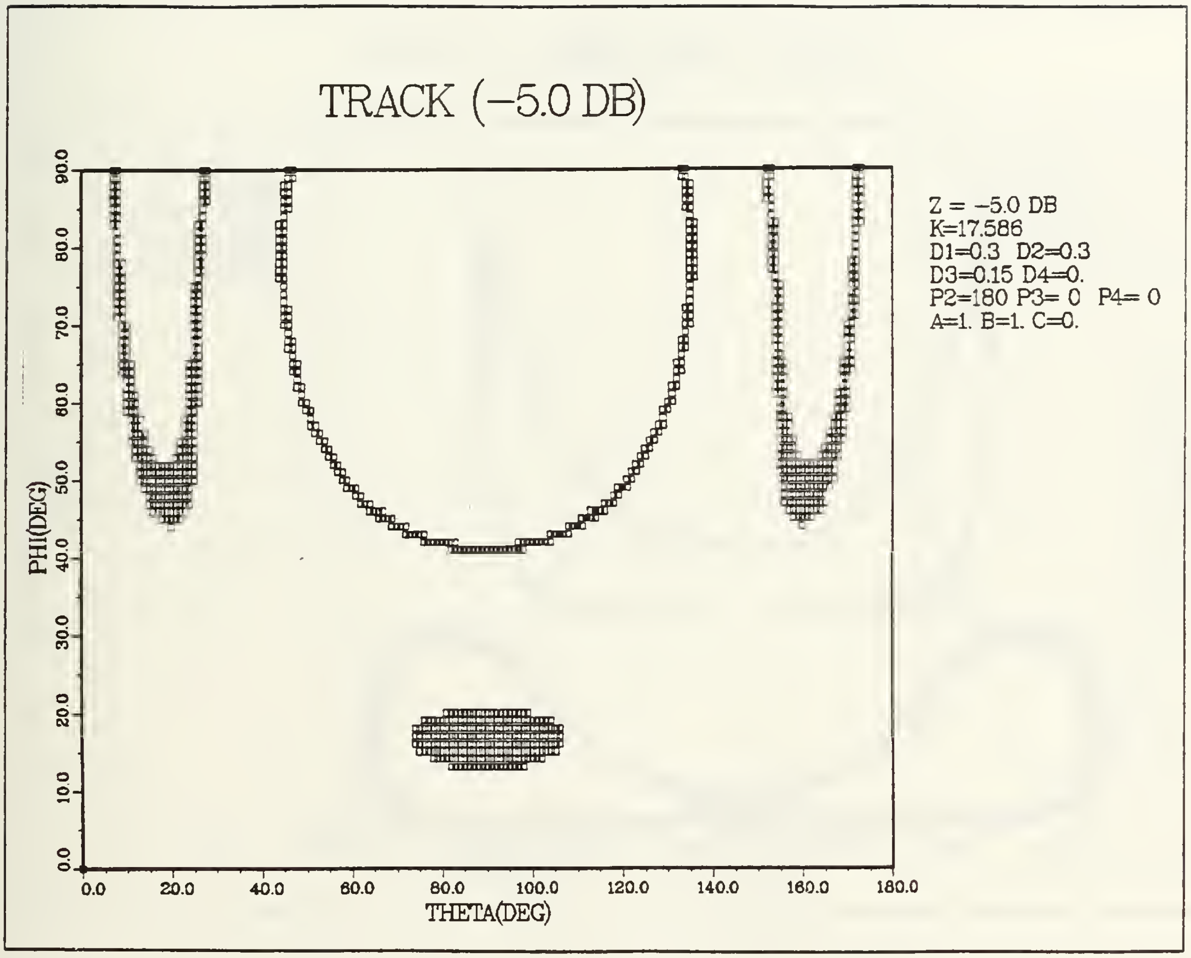

Figure 4.2d Track (-5 dB).

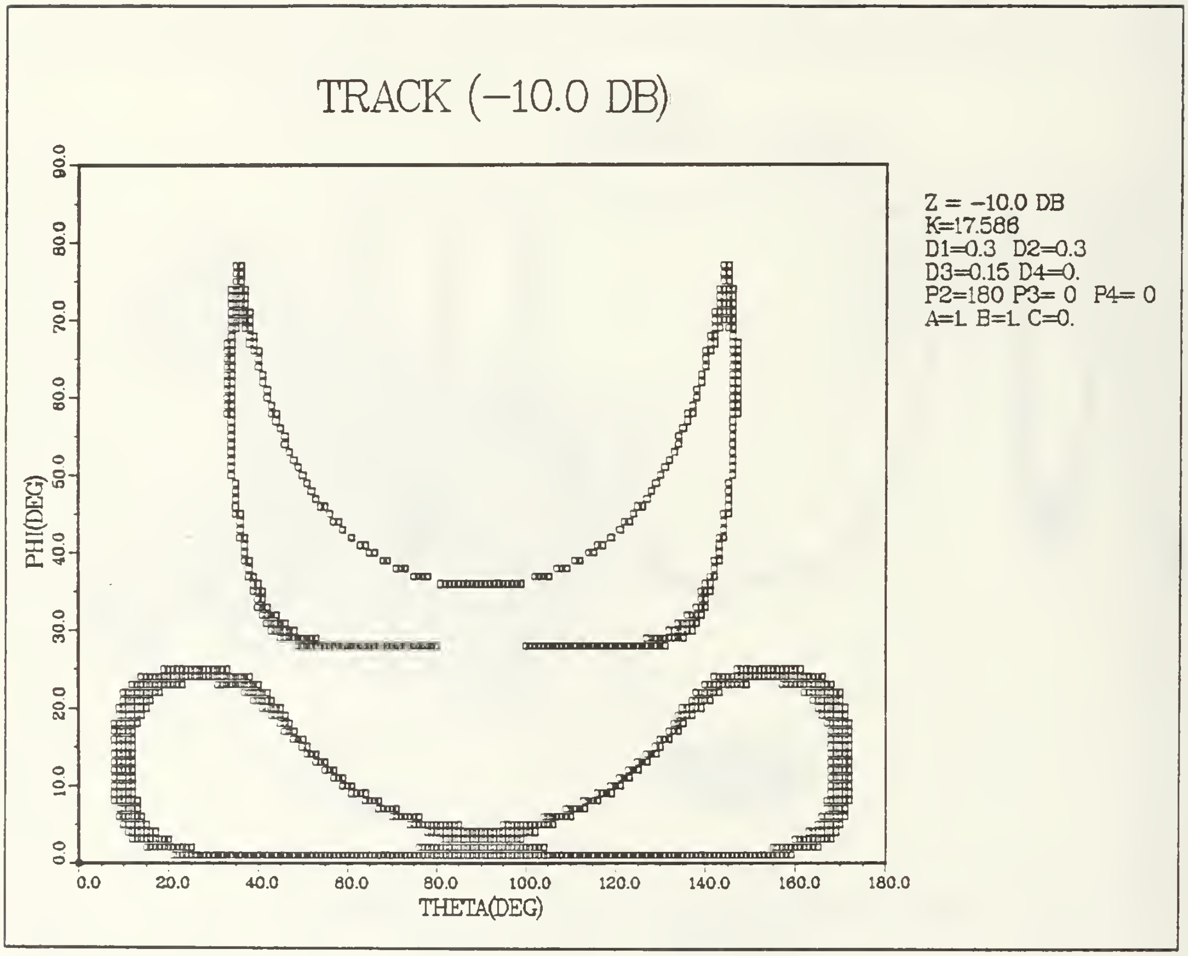

Figure 4.2e Track (-10 dB).

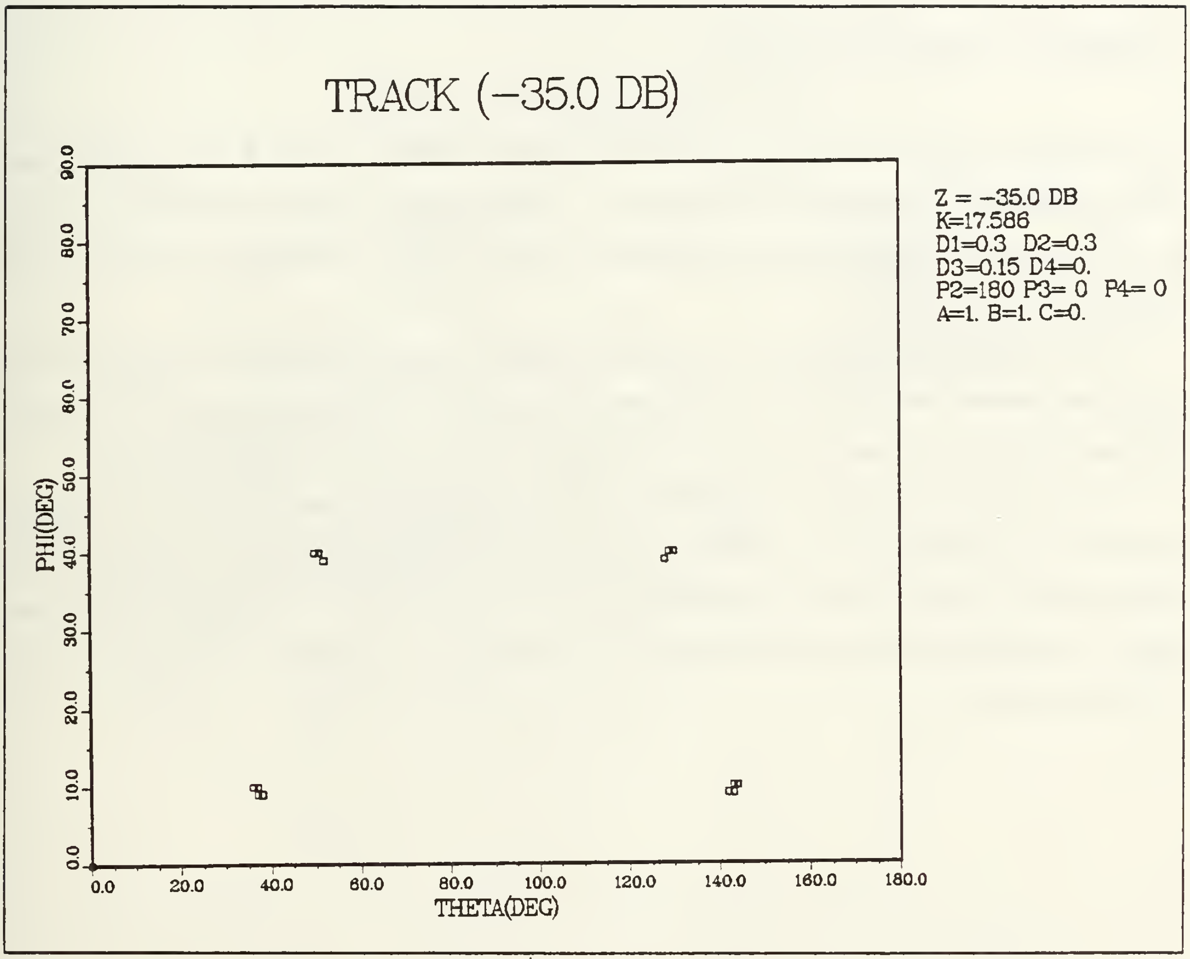

Figure 4.2f Track (-35 dB).

C. CASE 3

In this case, a doublet array is investigated. Referring to Figure 4.2a, this is the same as the first case except that the third and fourth elements are turned off and all elements are in phase.

For $kD_1 = kD_2 = kD_3 = kD_4 = 5.275,$

$\varphi_2 = \varphi_3 = \varphi_4 = 0,$

$A = 1, B = C = 0$

equation (2.37) can be simplified as

$$H(\theta,\Phi) = |\cos(5.275 \sin\theta\sin\Phi)|$$

As in cases 1 and 2, for $\theta = 0°, 35°, 90°$ and $\Phi = 90°$, we get F = 0, -0.058 and -5.459 respectively from hand-computation. These points are found in Figure 4.3a and, the two-dimensional plot again corresponds well in shape with Figure 4.3b from the experiment.

If we compare the shape of a two-dimensional plot (Figure 4.3a) with that of the three-dimensional plot (Figure 4.3c below), we see that the beam pattern of the two-dimensional graph is identical in the $\Phi = 0°$ plane of the three-dimensional plot.

For a constant value of $H(\theta,\Phi)$, we can follow the same procedure to get the equation for contour plots as in case 1 and 2. The resultant figures are Figures 4.3d, 4.3e and 4.3f. Figure 4.3d is drawn for the F values between -5.9 dB and -5.0 dB and Figure 4.3e is for the F values between -8.9 dB and -8.0 dB. Figure 4.3f is for F values less than -35.0 dB.

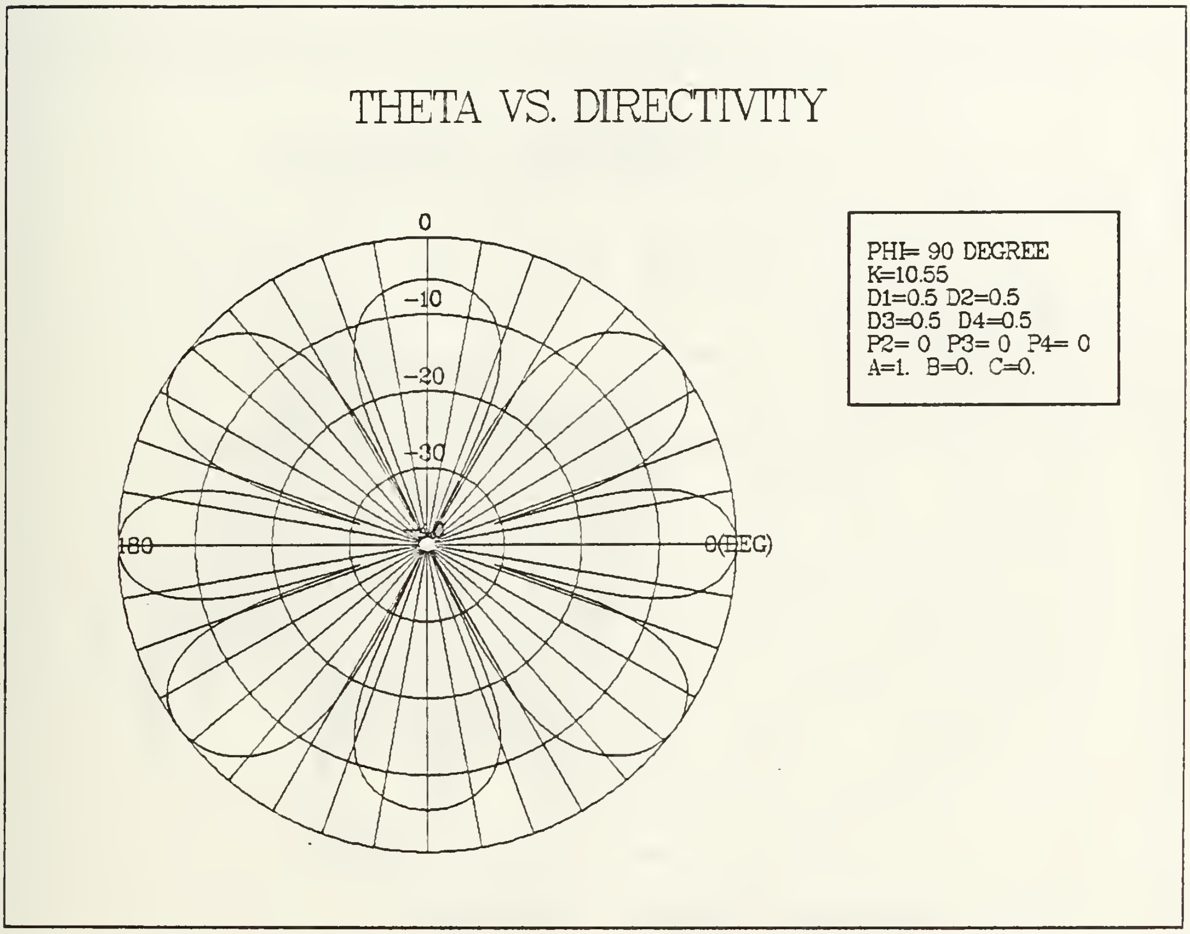

Figure 4.3a 2-D plot from the computer output.

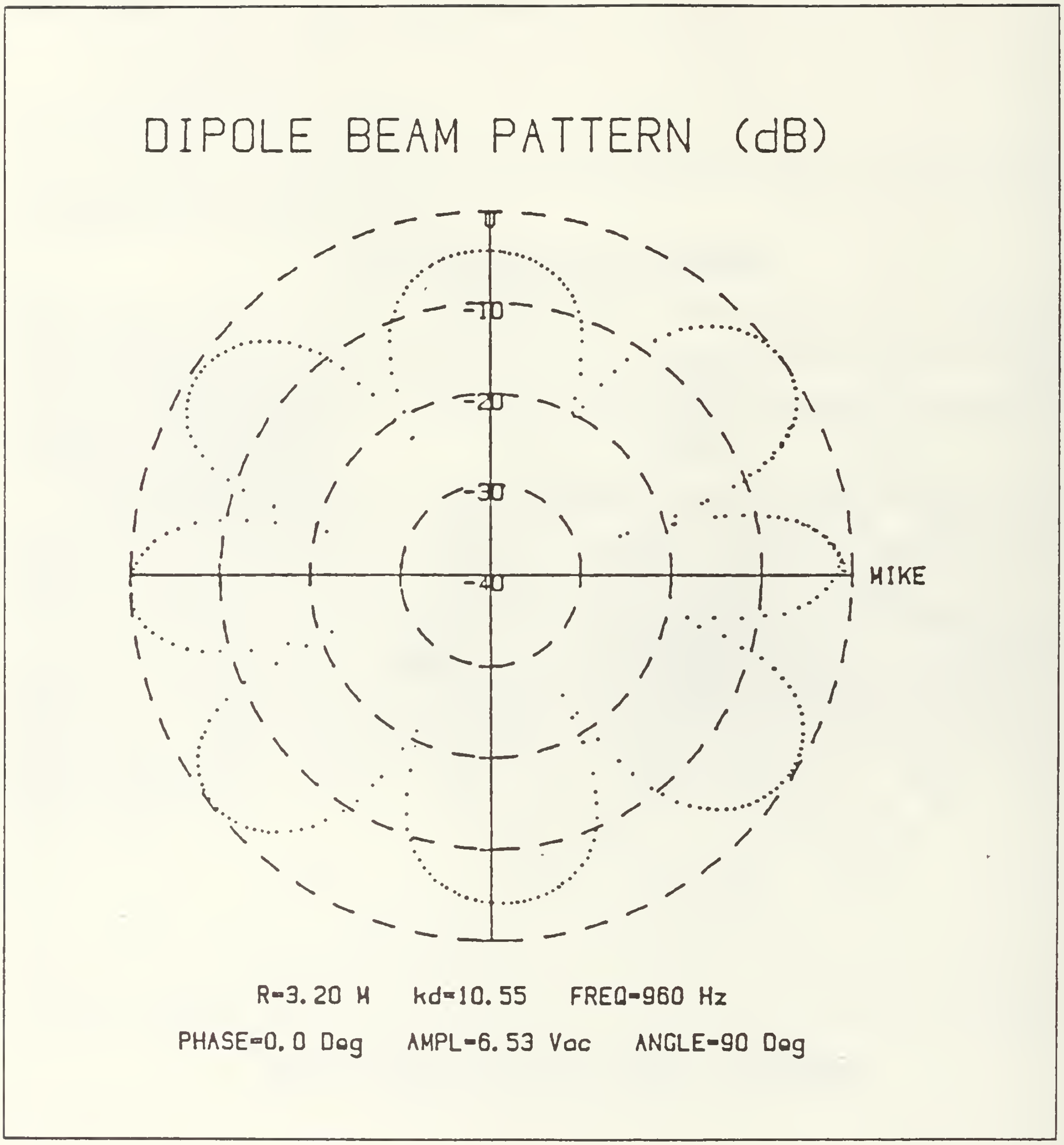

Figure 4.3b 2-D plot from the experiment.

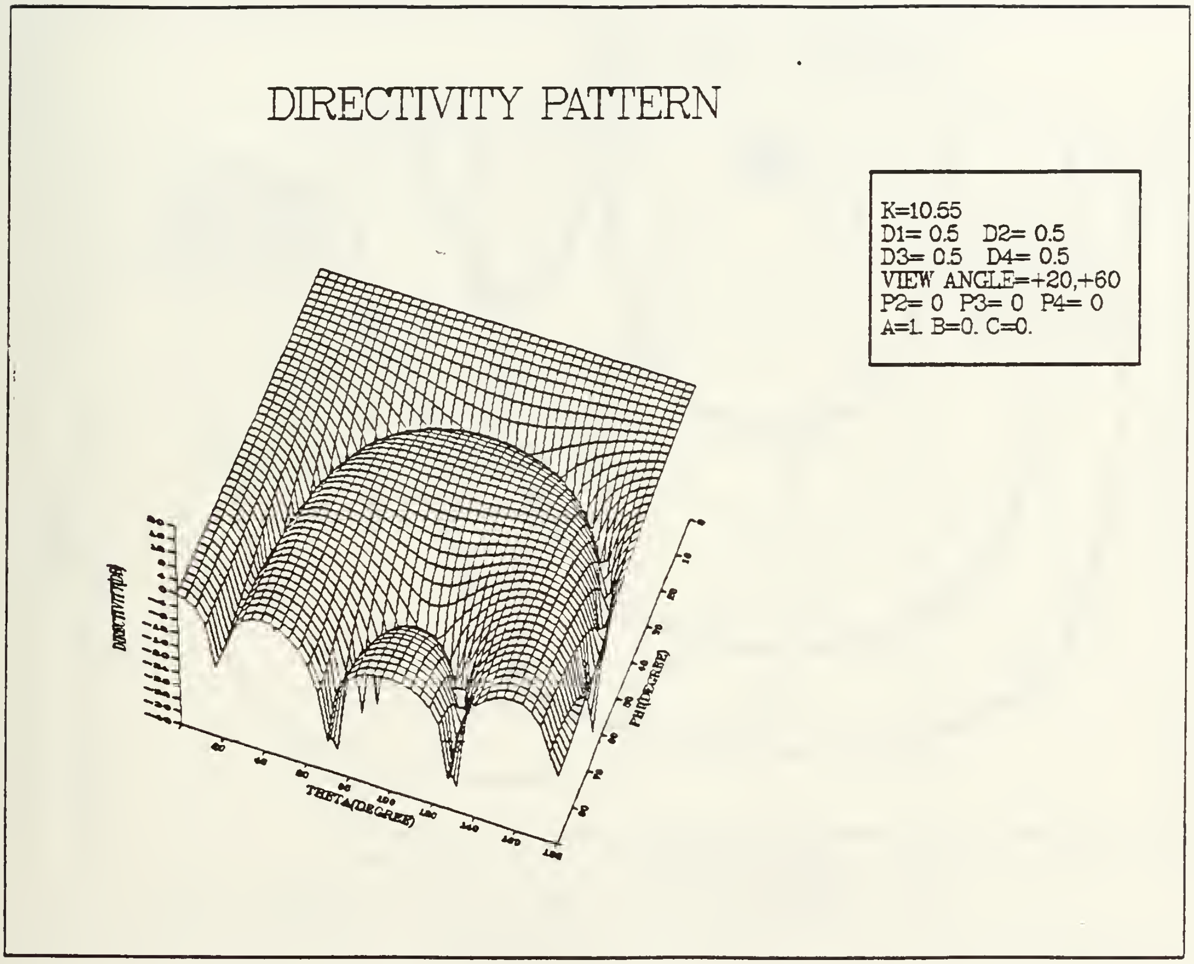

Figure 4.3c 3-D plot from the computer output.

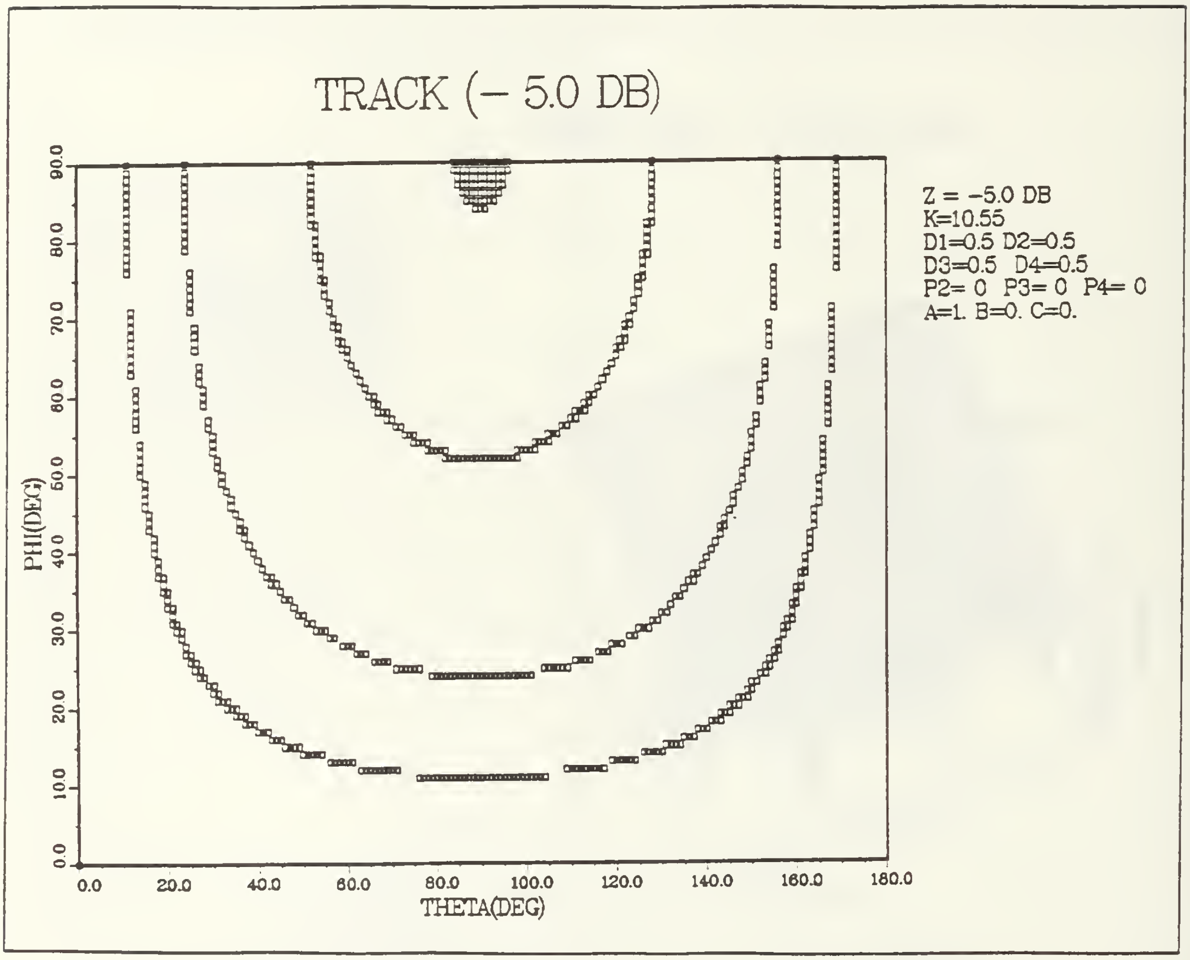

Figure 4.3d Track (-5 dB).

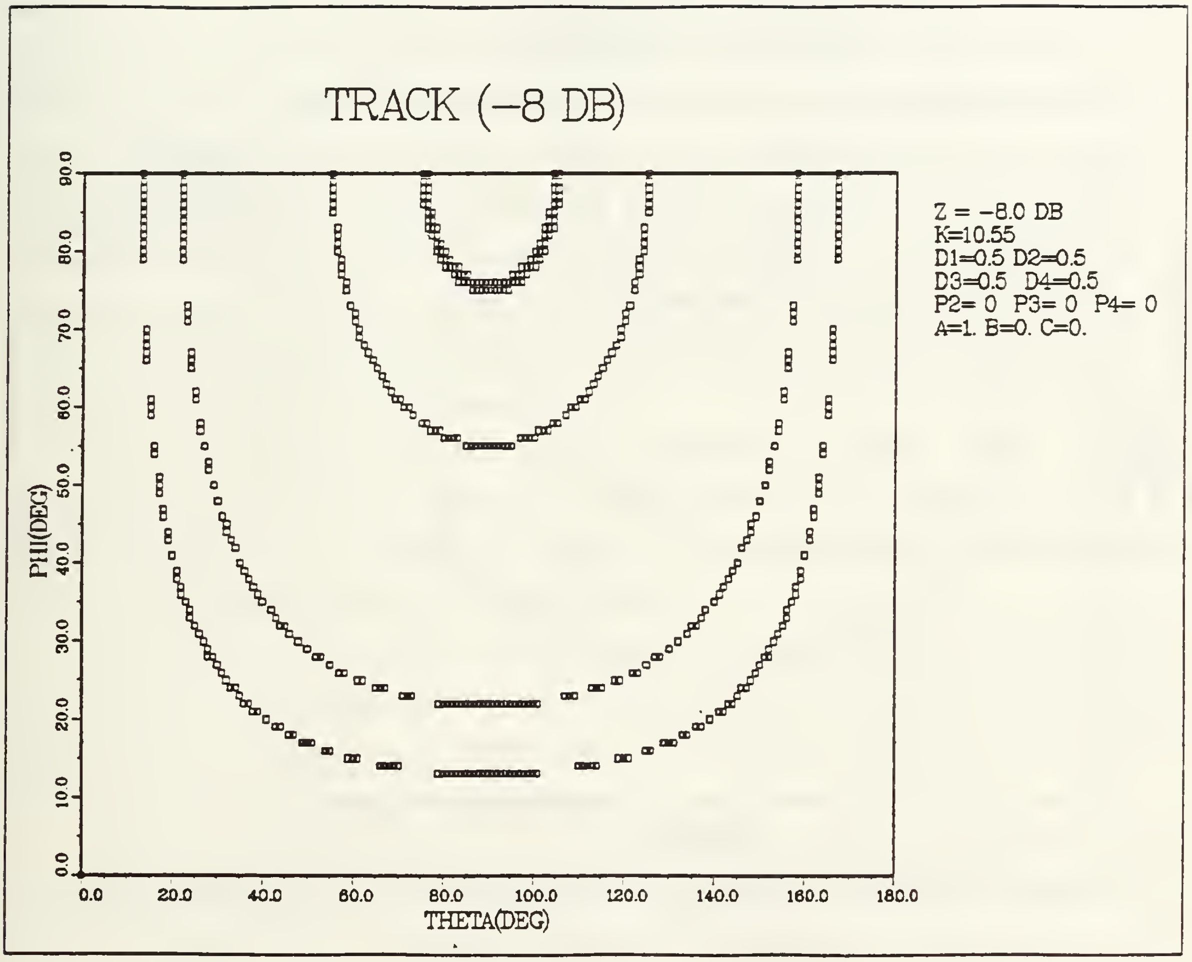

Figure 4.3e Track (-8 dB).

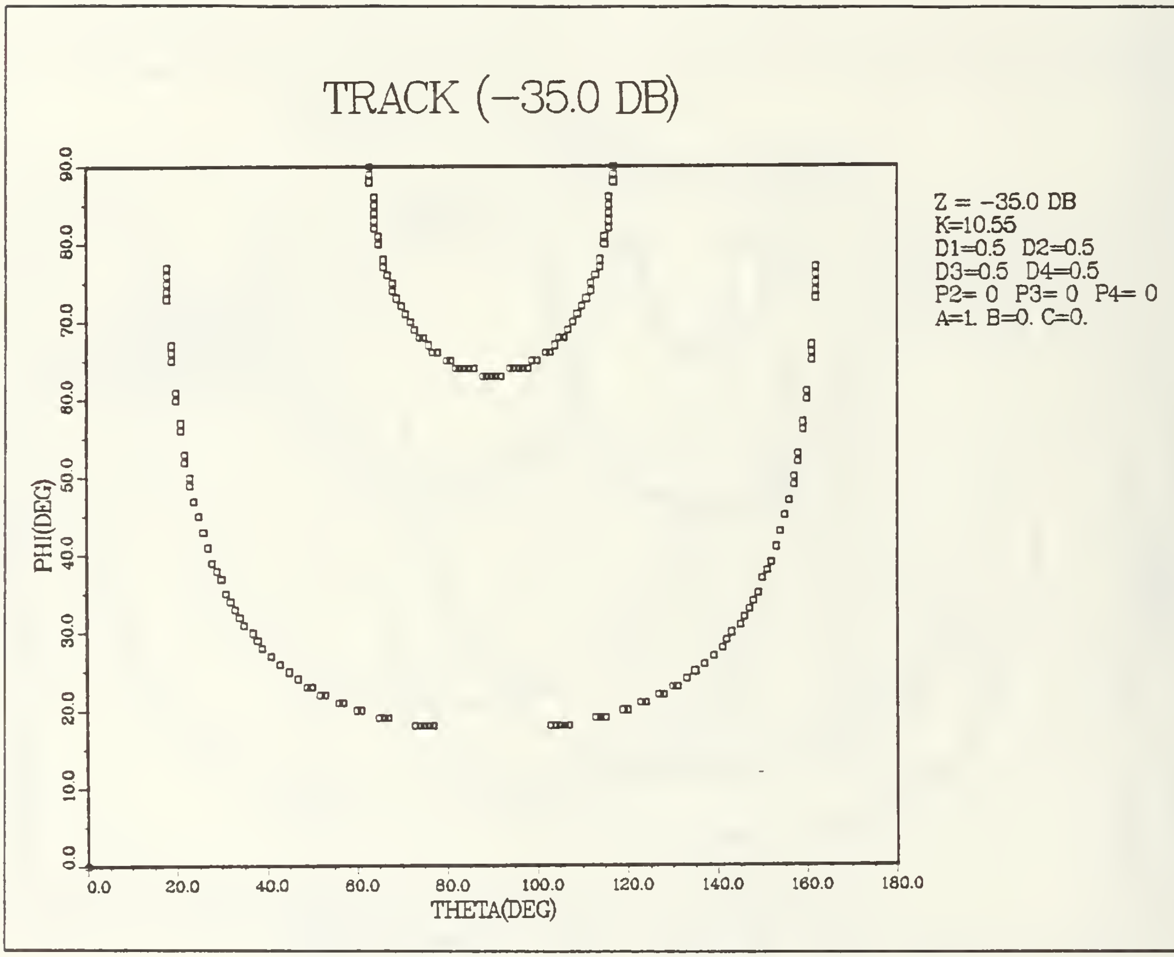

Figure 4.3f Track (-35 dB).

V. EVALUATION

In the last chapter, we looked at three simple cases. These established the accuracy of the five computer programs. For example, in comparisons between hand calculation and computer output, both sets of values were proven nearly identical. Again, due to the complexity of calculations, not all values were hand-calculated.

When a two-dimensional circular graph was compared with the selected hand-computed values, both groups of values were again virtually identical. As another test of the validity of the five computer programs, some of the computer generated two-dimensional plots were compared against those from an experiment [Ref. 9: p.18]. Visual comparisons of the two types of plots were similar in shape, but values in dB were somewhat different. These differences might be caused by the normalization of the angular dependance of the sound pressure. Also, because of the directivity of the real sources, there is a slight decrease in dB level of the experimental plots when the array pointed away from the receiver. However, they are small enough that the comparisons still seem quite reasonable.

Next, two-dimensional versus three-dimensional graphs were compared. Agreement here shows the programs are working properly. By varying the range of θ and Φ that are plotted, and also by varing the view angles, values and the shape of the curve can be visualized without great difficulty.

Tracks of certain directivity values were drawn using the modified P3D program (TRACE) and were compared to the three-dimensional plots. The shape of the resulting tracks corresponded well with those of the three-dimensional patterns, again showing proper functioning of the programs.

With all the comparisons made in Chapter IV, the five computer programs developed in this thesis were proven effective in predicting the directivity pattern in all directions of space with or without differences in the strength of the sources, inter-source distances and phases.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions are offered.

- The P2DICIR, P2DPCIR, P2DIFIX, P2DPFIX programs successfully predict the directivity beam pattern in two dimensions.
- The P3D program predicts and visualizes the directivity beam pattern in the three-dimension space.
- They allow the presentation of complete beam patterns, which contain considerable information, in a succinct, easy to comprehend and interpret form.

B. RECOMMENDATIONS

The following recommendations and areas of further investigation is suggested.

- Further studies for computer programs to visualize the beam pattern in the x-y-z space are needed to eliminate hidden lines in three-dimensional plotting.
- Transcendental equations need to be solved to get the contour plot for fixed F values.

APPENDIX A

BASIC PROGRAMS (HP COMPUTER)

```
**********************  INFORMATION  ********************************
*                                                                   *
*       THE OBJECTIVE OF THESE PROGRAMS IS TO CALCULATE AND         *
*       DRAW THE DIRECTIVITY PATTERN IN TWO-DIMENSION.              *
*       THIS IS WRITTEN IN BASIC LANGUAGE AND PLOTTER IS HP7090A.   *
*                                                                   *
*********************  VARIABLE DEFINITION  *************************
*                                                                   *
*       Z : DIRECTIVITY IN dB                                       *
*       P2 : PHASE (DEGREE) OF SOURCE A                             *
*       P3 : PHASE (DEGREE) OF SOURCE B                             *
*       P4 : PHASE (DEGREE) OF SOURCE C                             *
*       P5 : VARIABLE TO CHANGE DEGREE TO RADIAN                    *
*       P6 : RADIAL VALUE OF P1                                     *
*       P7 : RADIAL VALUE OF P2                                     *
*       P8 : RADIAL VALUE OF P3                                     *
*       K : WAVE NUMBER                                             *
*       D : INTER-SOURCE DISTANCE                                   *
*       P : PHI IN DEGREE                                           *
*       I : THETA IN DEGREE                                         *
*       PI : 3.1415917                                              *
*                                                                   *
*********************************************************************

*********************************************************************
                  HP PROGRAM FOR THE RECTANGULAR GRAPH
*********************************************************************


--------------------------------------------------------------------
                        INPUT PARAMETERS
--------------------------------------------------------------------

5 OPTION BASE 1
6 RAD
10 DIM Z(360)
20 DISP "WHAT IS THE VALUE OF KD?  KD=  " !          KD=K*D
30 INPUT KD
60 DISP "WHAT IS THE VALUE OF P2(DEG)? P2= "!        P2=PHASE OF A
61 INPUT P2
62 DISP "WHAT IS THE VALUE OF P3(DEG)? P3= " !       P3=PHASE OF B
63 INPUT P3
64 DISP "WHAT IS THE VALUE OF P3(DEG)? P4= " !       P4=PHASE OF C
65 INPUT P4
66 DISP "WHAT IS THE VALUE OF A?  A=  "
67 INPUT A
68 DISP "WHAT IS THE VALUE OF B?  B=  "
69 INPUT B
70 DISP "WHAT IS THE VALUE OF C?  C=  "
71 INPUT C
72 DISP "IS P FIXED? (YES;AN=1 , NO;AN=0)  AN=  "
73 INPUT AN
74 IF AN=1 THEN DISP "WHAT IS THE VALUE OF P(DEG)? P= "ELSE GOTO 76
75 INPUT P
76 DISP "IS I FIXED? (YES;ANS=1 , NO;ANS=0)  ANS= "
77 INPUT ANS
78 IF ANS=1 THEN DISP "WHAT IS THE VALUE OF I(DEG)? I= "ELSE GOTO 82
79 INPUT I
82 DISP "**************************************************"
83 IF AN=0 AND ANS=0 THEN GOTO 86
84 IF AN=0 AND ANS=1 THEN GOTO 90
85 IF AN=1 AND ANS=0 THEN GOTO 93
86 DISP "*";"K*D=";KD," ","*"
87 DISP "*PHASE OF A(DEG)=";P2;"PHASE OF B(DEG)=";P3;"PHASE OF C(DEG)=";P4,"*"
88 DISP "*";"A=";A," B=";B,"C=";C,"*" @ GOTO 99
90 DISP "*";"K*D=";KD,"  I(DEG)=";I," ","*"
91 DISP "*PHASE OF A(DEG)=";P2;"PHASE OF B(DEG)=";P3;"PHASE OF C(DEG)=";P4,"*"
92 DISP "*";"A=";A," B=";B,"C=";C,"*" @ GOTO 103
93 DISP "*";"K*D=";KD,"  I(DEG)=";I," ","*"
```

```
94 DISP "*PHASE OF A(DEG)=";P2;"PHASE OF B(DEG)=";P3;"PHASE OF C(DEG)=";P4,"*"
95 DISP "*";"A=";A," B=";B,"C=";C,"*" @ GOTO 107
99 DISP "***************************************************"
100 DISP " "
101 DISP "  ";" THETA";"    PHI","           DIRECTIVITY"
102 FOR P=1 TO 360 @ GOTO 110
103 DISP "***************************************************"
104 DISP " "
105 DISP "  ";" THETA";"    PHI","           DIRECTIVITY"
106 FOR P=1 TO 360 @ GOTO 115
107 DISP "***************************************************"
108 DISP " "
109 DISP "  ";" THETA";"    PHI","           DIRECTIVITY"
```

MAIN PROGRAM

```
110 FOR I=1 TO 360
115 P5=PI /180
116 P6=P2*P5 @ P7=P3*P5 @ P8=P4*P5
117 Q=P-90
118 Q1=SIN (Q*P5)
119 I1=SIN (I*P5)
120 Q2=SIN (P*P5)
121 W1=KD*I1*Q2/2
121 W2=KD*I1*Q1/2
127 W=COS (W1)+A*COS (W1+P6)+B*COS (W2-P7)+C*COS (W2+P8)
128 G=SIN (W1)-A*SIN (W1+P6)+B*SIN (W2-P7)-C*SIN (W2+P8)
130 H=SQR (W**2+G**2)/(1+A+B+C)
140 Z(P)=20*LGT (H)
143 T=20*LGT (ABS (SIN (.5*KD*I1)))
150 DISP USING 153 ; I,P,Z(P)
153 IMAGE 5X,3D.D,5X,3D.D,15X,SDDD.DDD,15X,SDDD.DDD
155 !  IF Z(I)<-20 THEN I=I+.1 @ GOTO 119
156 !  I= IP(I)
157 !  IF Z(P)<-20 THEN P=P+.1 @ GOTO 117
158 !  P= IP(P))
160 IF AN=1 AND ANS=0 THEN GOTO 163 ELSE GOTO 161
161 IF AN=0 AND ANS=1 THEN GOTO 164 ELSE GOTO 163
162 NEXT P @ GOTO 96
163 !  NEXT I
164 NEXT P
```

PLOTTING WITH HP7090A

```
170 PLOTTER IS 705
180 CLEAR
190 GCLEAR
200 GRAME
210 LOCATE 15,145,10,80
220 SCALE 0,390,-240,0
230 CLIP 0,360,0,-240
240 AXES 5,5,0,-240,10,10,2
250 LINE TYPE 1
260 GRID 20,-20
270 FRAME
280 LORG 6
290 CSIZE 4
300 FOR I=0 TO 360 STEP 40
310     MOVE I,-241
320     LABEL I
330 NEXT I
340 LORG 8
350 FOR I=-240 TO 0 STEP 40
360     MOVE -1,I
370     LABEL I
380 NEXT I
390 CSIZE 5
400 LORG 5
410 MOVE 180,40
420 CSIZE *
430 PEN 2
440 LABEL "PHI VS DIRECTIVITY"
450 LORG 5
460 MOVE 180,20
470 CSIZE 4
480 LABEL "(THETA = 45 DEGREE)"
490 CSIZE 5
500 LORG 5
510 MOVE 180,-26-
520 CSIZE 4
```

```
530 LABEL "PHI(DEG)"
540 LOIR 90
550 MOVE -30,-120
560 DEG
570 LDIR 90
580 CSIZE 4
590 LABEL "DIRECTIVITY(dB)"
600 CSIZE 5
610 MOVE 0,0
620 FOR P=1 TO 360
630     DRAW P,Z(P)
640 NEXT P
650 PEN 0
700 END
 117392
```

```
**********************************************************************
                              HP PROGRAM FOR CIRCULAR GRAPH
**********************************************************************
```

```
----------------------------------------------------------------------
                         INPUT PARAMETERS
----------------------------------------------------------------------

5 OPTION BASE 1
6 RAD
10 DIM X(360)
11 DIM Y(360)
12 DIM Z(360)
20 DISP "WHAT IS THE VALUE OF KD?  KD=  " !           KD=K*D
30 INPUT KD
60 DISP "WHAT IS THE VALUE OF P2(DEG)? P2= "!         P2=PHASE OF A
61 INPUT P2
62 DISP "WHAT IS THE VALUE OF P3(DEG)? P3= " !        P3=PHASE OF B
63 INPUT P3
64 OISP "WHAT IS THE VALUE OF P4(DEG)? P4= " !        P4=PHASE OF C
65 INPUT P4
66 DISP "WHAT IS THE VALUE OF A?  A=  "
67 INPUT A
68 DISP "WHAT IS THE VALUE OF B?  B=  "
69 INPUT B
70 DISP "WHAT IS THE VALUE OF C?  C=  "
71 INPUT C
72 DISP "IS P FIXED? (YES;AN=1 , NO;AN=0)  AN=  "
73 INPUT AN
74 IF AN=1 THEN DISP "WHAT IS THE VALUE OF P(DEG)? P= "ELSE GOTO 76
75 INPUT P
76 DISP "IS I FIXED? (YES;ANS=1 , NO;ANS=0)  ANS= "
77 INPUT ANS
78 IF ANS=1 THEN DISP "WHAT IS THE VALUE OF I(DEG)? I= "ELSE GOTO 82
79 INPUT I
82 DISP "**************************************************"
83 IF AN=0 AND ANS=0 THEN GOTO 86
84 IF AN=0 ANO ANS=1 THEN GOTO 90
85 IF AN=1 AND ANS=0 THEN GOTO 93
86 DISP "*";"K*O=";KD," ","*"
87 DISP "*PHASE OF A(DEG)=";P2;"PHASE OF B(DEG)=";P3;"PHASE OF C(DEG)=";P4,"*"
88 DISP "*";"A=";A," B=";B,"C=";C,"*" @ GOTO 99
90 DISP "*";"K*O=";KD,"  I(DEG)=";I," ","*"
91 OISP "*PHASE OF A(DEG)=";P2;"PHASE OF B(DEG)=";P3;"PHASE OF C(DEG)=";P4,"*"
92 DISP "*";"A=";A," B=";B,"C=";C,"*" @ GOTO 103
93 DISP "*";"K*O=";KD,"  I(OEG)=";I," ","*"
94 DISP "*PHASE OF A(DEG)=";P2;"PHASE OF B(DEG)=";P3;"PHASE OF C(DEG)=";P4,"*"
95 DISP "*";"A=";A," B=";B,"C=";C,"*" @ GOTO 107
99 DISP "**************************************************"
100 DISP " "
101 DISP "  ";" THETA";"    PHI","           DIRECTIVITY"
102 FOR P=1 TO 360 @ GOTO 110
103 DISP "**************************************************"
104 DISP " "
105 DISP "  ";" THETA";"    PHI","           DIRECTIVITY"
106 FOR P=1 TO 360 @ GOTO 115
107 DISP "**************************************************"
108 DISP " "
109 DISP "  ";" THETA";"    PHI","           DIRECTIVITY"

----------------------------------------------------------------------
                           MAIN PROGRAM
----------------------------------------------------------------------

110 FOR I=1 TO 360
115 P5=PI /180
```

```
116 P6=P2*P5 ∂ P7=P3*P5 ∂ P8=P4*P5
117 Q=P-90
118 Q1=SIN (Q*P5)
119 I1=SIN (I*P5)
120 Q2=SIN (P*P5)
121 W1=KD*I1*Q2/2
121 W2=KD*I1*Q1/2
127 W=COS (W1)+A*COS (W1+P6)+B*COS (W2-P7)+C*COS (W2+P8)
128 G=SIN (W1)-A*SIN (W1+P6)+B*SIN (W2-P7)-C*SIN (W2+P8)
130 H=SQR (W**2+G**2)/(1+A+B+C)
140 Z(I)=20*LGT (H)+240
141 X(I)=Z(I)*COS (I*P5)
142 Y(I)=Z(I)*SIN (I*P5)
143 T=20*LGT (ABS (SIN (.5*KD*I1)))
150 DISP USING 153 ; I,P,Z(P)
153 IMAGE 5X,SDDD.DDD,15X,SDDD.DDD
155 !  IF Z(I)<-20 THEN I=I+.1 ∂ GOTO 119
156 !  I= IP(I)
157 !  IF Z(P)<-20 THEN P=P+.1 ∂ GOTO 117
158 !  P= IP(P))
160 IF AN=1 AND ANS=0 THEN GOTO 163 ELSE GOTO 161
161 IF AN=0 AND ANS=1 THEN GOTO 164 ELSE GOTO 163
162 NEXT P ∂ GOTO 96
163 NEXT I
164 !  NEXT P
```

PLOTTING WITH HP7090A

```
170 PLOTTER IS 705
180 CLEAR
190 GCLEAR
200 GRAME
210 LOCATE 25,120,5,80
220 SCALE -260,320,-220,240
230 CLIP -240,240,-240,240
235 XAXIS 0,20,-240,240
240 YAXIS 0,20,-240,240
250 LINE TYPE 1
270 FRAME
280 LORG 6
290 CSIZE 4
300 FOR I=0 TO 360 STEP 40
310     MOVE I,-5
320     LABEL I-240
321     MOVE -1,I
322     LABEL I-240
330 NEXT I
340 LORG 6
341 MOVE 0,-5
342 LABEL -240
350 FOR I=-240 TO -60 STEP 60
360     MOVE -1,I
370     LABEL -240-I
371     MOVE I,-5
372     LABEL -240-I
375 NEXT I
380 MOVE 0,0
381 FOR I=0 TO 240 STEP 60
382     FOR J=0 TO 360
383         X=I*COS (J*PI /180)
384         Y=I*SIN (J*PI /180)
385         DRAW X,Y
386     NEXT J
387 NEXT I
390 CSIZE 5
400 LORG 5
410 MOVE 0,310
420 CSIZE 8
430 PEN 2
440 LABEL "THETA VS DIRECTIVITY"
450 LORG 50
460 MOVE 0,285
470 CSIZE 4
480 LABEL "(PHI = 90 DEGREE)"
490 CSIZE 5
500 LORG 5
510 MOVE 300,0
520 CSIZE 4
530 LABEL "0(DEG)"
550 MOVE -300,0
580 CSIZE 4
590 LABEL "180(DEG)"
```

```
610 MOVE 0,0
620 FOR I-1 TO 360
630     DRAW X(I),Y(I)
640 NEXT I
650 PEN 0
700 END
 111174
```

APPENDIX B

P2DIFIX, P2DPFIX, P2DICIR AND P2DPCIR

```
*********************** INFORMATION **********************************
*                                                                    *
*        THE OBJECTIVE OF THESE PROGRAMS IS TO CALCULATE AND         *
*        DRAW THE DIRECTIVITY PATTERN IN TWO-DIMENSION.              *
*        THE DRAWING METHOD IS THE SUBROUTINE CURVE OF DISSPLA.      *
*        I(θ) AND P(Φ) CAN BE USED INTERCHANGEABLY FOR               *
*        P2DPFIX AND P2DICIR PROGRAMS.                               *
*                                                                    *
********************** VARIABLE DEFINITION **************************
*                                                                    *
*        Z : DIRECTIVITY IN dB                                       *
*        P1 : PHASE (DEGREE) OF SOURCE A                             *
*        P2 : PHASE (DEGREE) OF SOURCE B                             *
*        P3 : PHASE (DEGREE) OF SOURCE C                             *
*        P4 : VARIABLE TO CHANGE DEGREE TO RADIAN                    *
*        P5 : RADIAL VALUE OF P1                                     *
*        P6 : RADIAL VALUE OF P2                                     *
*        P7 : RADIAL VALUE OF P3                                     *
*        K : WAVE NUMBER                                             *
*        D1 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE 1   *
*        D2 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE A   *
*        D3 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE B   *
*        D4 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE C   *
*        P : PHI IN DEGREE                                           *
*        I : THETA IN DEGREE                                         *
*        PH : PHI IN RADIAN                                          *
*        TH : THETA IN RADIAN                                        *
*        PHI : DUMMY VARIABLE OF PHI                                 *
*        THETA : DUMMY VARIABLE OF THETA                             *
*        PI : 3.1415917                                              *
*                                                                    *
********************** VARIABLE DECLARATION *************************
C
C
**********************************************************************
            PROGRAM FOR THE TWO-DIMENSIONAL RECTANGULAR GRAPH
**********************************************************************
C
      DIMENSION PHI(361),THETA(361),Z(360)
      REAL P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI,a,b,c
      INTEGER P,P1,P2,P3,I
C
C---------------------------------------------------------------------
C                          INPUT PARAMETERS
C---------------------------------------------------------------------
C
      PI=3.1415917
      K=5.5
      D1=1.
      D2=1.
      D3=1.
      D4=1.
      P1= 180
      P2= 0
      P3= 180
      A = 1.
      B = 1.
      C = 1.
      I = 25: USE P FOR P2DPFIX
C
C---------------------------------------------------------------------
C                            MAIN PROGRAM
C---------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
c     DO 100 I=1,360: MOVE C TO LINE NO. 76 FOR P2DPFIX
         DO 200 P=1,360
```

```
          TH=I*P4
          PH=P*P4
          W1=K*D1*SIN(PH)*SIN(TH)
          W2=K*D2*SIN(PH)*SIN(TH)_P5
          W3=K*D3*SIN(TH)*COS(PH)-P6
          W4=K*D4*SIN(TH)*COS(PH)+P7
          W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
          G=SIN(W1)-A*SIN(W2)-B*SIN(W3)+C*SIN(W4)
          H=SQRT(W*W+G*G)/(1+A+B+C)
          Z(P)=20*ALOG10(H)
          IF(Z(P).LE.-40.) THEN
              Z(P)=-40
          ELSE
              Z(P)=Z(P)
          END IF
          THETA(P)=I
          PHI(P)=P
          WRITE(8,1) PHI(P),Z(P)
1         FORMAT(2X,2(E10.3,5X))
200     CONTINUE
100   CONTINUE
C
C------------------------------------------------------------------------
C         A PROGRAM FOR PLOTTING BY SHERPAOR BY TEK618
C------------------------------------------------------------------------
C
      CALL MEDBUF
      CALL COMPRS
C     CALL TEK618: MOVE C TO DRAW USING TEK618
      CALL PHYSOR(1.,1.)
      CALL PAGE(15.5,12.)
      CALL AREA2D(10.5,9.1)
      CALL FRAME
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL XNAME('PHI(DEG)  $',10)
      CALL YNAME('DIRECTIVITY(DB)$',15)
      CALL YTICKS(8)
      CALL XTICKS(8)
      CALL GRAF(0,40,360,-40,4,0)
      CALL GRID(2,2)
      CALL CURVE(PHI,Z,359,0)
      CALL MESSAG('THETA=25 DEGREE',15,11.,8.5)
      CALL MESSAG('K=5.5',5,11.,8.2)
      CALL MESSAG('D1=1. D2=1.',11,11.,7.9)
      CALL MESSAG('D3=1. D4=1.',11,11.,7.6)
      CALL MESSAG('P2=180 P3=0 P4=180',18,11.,7.3)
      CALL MESSAG('A=1. B=1. C=1.',14,11.,7.0)
      CALL RESET('HEIGHT')
      CALL HEIGHT(.4)
      CALL MESSAG('PHI VS. DIRECTIVITY',19,3.1,9.8)
      CALL RESET('ALL')
      CALL NOCHEK
      CALL ENDGR(0)
      CALL PHYSOR(11.85,7.6)
      CALL AREA2D(3.5,2.5)
      CALL FRAME
      CALL ENDPL(0)
      STOP
      END
C
C
************************************************************************
     PROGRAM FOR THE CIRCULAR TWO-DIMENSIONAL GRAPH
************************************************************************
C
      DIMENSION PHI(360),R(360),THETA(360),Z(360),X(4),Y(4)
      REAL P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI,a,b,c
      INTEGER P,P1,P2,P3,I,Q
C
C------------------------------------------------------------------------
C                          INPUT PARAMETERS
C------------------------------------------------------------------------
C
      PI=3.1415917
      K=5.5
      D1=1.
      D2=1.
      D3=1.
      D4=1.
      P1= 180
      P2= 0
      P3= 180
      A = 1.
```

```
      B = 1.
      C = 1.
      I = 25: USE P FOR P2DPCIR
C
C-----------------------------------------------------------------------
C                              MAIN PROGRAM
C-----------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
C     DO 100 I=0,360: MOVE C TO LINE NO. 174 FOR P2DICIR
         DO 200 P=0,360
            TH=I*P4
            PH=P*P4
            W1=K*D1*SIN(PH)*COS(TH)
            W2=K*D2*SIN(PH)*COS(TH)+P5
            W3=K*D3*SIN(TH)*COS(PH)-P6
            W4=K*D4*SIN(TH)*COS(PH)+P7
            W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
            G=SIN(W1)-A*SIN(W2)+B*SIN(W3)-C*SIN(W4)
            H=SQRT(W*W+G*G)/(1+A+B+C)
            Z(P)=20*ALOG10(H)
            IF(Z(P).LE.-40.) THEN
                Z(P)=0.
            ELSE
                Z(P)=40.+Z(P)
            END IF
            THETA(P)=I
            PHI(P)=P
            WRITE(8,1) PHI(P),Z(P)
1           FORMAT(2X,2(E10.3,5X))
200      CONTINUE
100   CONTINUE
C
C-----------------------------------------------------------------------
C         A PROGRAM FOR PLOTTING BY SHERPAOR BY TEK618
C-----------------------------------------------------------------------
C
      CALL MEDBUF
      CALL COMPRS
C     CALL TEK618: MOVE C TO THE UPPER LINE WHEN DRAWING WITH TEK618
      CALL PHYSOR(1.5,1.)
      CALL PAGE(15.5,12.)
      CALL AREA2D(8.,8.)
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL POLAR(3.1415917/180.,10.,4.,4.)
      CALL GRID(1,1)
      CALL CURVE(PHI,Z,360,0)
      CALL MESSAG('THETA=25 DEGREE',15,9.7,7.7)
      CALL MESSAG('K=5.5',5,9.7,7.4)
      CALL MESSAG('D1=1. D2=1.',11,9.7,7.1)
      CALL MESSAG('D3=1. D4=1.',11,9.7,6.8)
      CALL MESSAG('P2=180 P3=0 P4=180',18,9.7,6.5)
      CALL MESSAG('A=1. B=1. C=1.',14,9.7,6.2)
      CALL MESSAG('0',1,3.9,8.1)
      CALL MESSAG('-10',3,3.7,7.1)
      CALL MESSAG('-20',3,3.7,6.1)
      CALL MESSAG('-30',3,3.7,5.1)
      CALL MESSAG('-40',3,3.7,4.1)
      CALL MESSAG('0(DEG)',6,7.6,3.9)
      CALL MESSAG('180',3,0.,3.9)
      CALL RESET('HEIGHT')
      CALL HEIGHT(.4)
      CALL MESSAG('PHI VS. DIRECTIVITY',19,3.0,9.5)
      CALL RESET('ALL')
      CALL NOCHEK
      CALL ENDGR(0)
      CALL PHYSOR(10.95,6.8)
      CALL AREA2D(3.5,2.5)
      CALL FRAME
      CALL DONEPL
      STOP
      END
```

APPENDIX C

PROGRAM FOR THE 3-D GRAPH USING SURMAT ABOUT X-Y PLANE

```
*********************** INFORMATION **********************************
*                                                                     *
*        THE OBJECTIVE OF THIS PROGRAM IS TO CALCULATE AND DRAW       *
*        THE DIRECTIVITY PATTERN IN THREE-DIMENSION.                  *
*        THE DRAWING METHOD IS THE SUBROUTINE SURMAT OF DISSPLA.      *
*                                                                     *
********************** VARIABLE DEFINITION ***************************
*                                                                     *
*        Z : DIRECTIVITY IN dB                                        *
*        ZMM : DOUBLE MATRIX TO GET X-Y PLANE                         *
*        ZM : DUMMY VARIABLE OF Z                                     *
*        P1 : PHASE (DEGREE) OF SOURCE A                              *
*        P2 : PHASE (DEGREE) OF SOURCE B                              *
*        P3 : PHASE (DEGREE) OF SOURCE C                              *
*        P4 : VARIABLE TO CHANGE DEGREE TO RADIAN                     *
*        P5 : RADIAL VALUE OF P1                                      *
*        P6 : RADIAL VALUE OF P2                                      *
*        P7 : RADIAL VALUE OF P3                                      *
*        K : WAVE NUMBER                                              *
*        D1 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE 1    *
*        D2 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE A    *
*        D3 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE B    *
*        D4 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE C    *
*        PHI : PHI IN DEGREE                                          *
*        I : THETA IN DEGREE                                          *
*        PH : PHI IN RADIAN                                           *
*        TH : THETA IN RADIAN                                         *
*        PI : 3.1415917                                               *
*                                                                     *
********************** VARIABLE DECLARATION **************************
         DIMENSION Z(8100),ZMM(90,90)
         REAL P,T,R,X,Y,ZM,a,b,c
         REAL P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI
         INTEGER PHI,P1,P2,P3,I
c
c
-----------------------------------------------------------------------
                     PROGRAM FOR THE UPPER HEMISPHERE
-----------------------------------------------------------------------
c
C
c----------------------------------------------------------------------
C          A PROGRAM FOR PLOTTING BY SHERPAOR BY TEK618
C----------------------------------------------------------------------
C
      CALL COMPRS
C     CALL TEK618: MOVE C TO THE UPPER LINE WHEN DRAWING WITH TEK618
      CALL RESET (3HALL)
      CALL PAGE(15.,9.)
      CALL PHYSOR(1.,3.)
      CALL SCMPLX
      CALL AREA2D(14.,8.)
      CALL X3NAME(1H ,1)
      CALL Y3NAME(1H ,1)
      CALL Z3NAME(1H ,1)
      CALL VOLM3D (17.,17.,17.)
      CALL VUANGL(+20.,+20.,500.)
      CALL INTAXS
      CALL ZAXANG (-90.)
      CALL GRAF3D(0.,10.,80.,0.,10.,80.,0.,10.,40.)
      CALL BLSUR
      CALL BGNMAT(90,90)
C
C----------------------------------------------------------------------
C                         INPUT PARAMETERS
C----------------------------------------------------------------------
C
      PI=3.1415917
      K=PI
      D1=1.
```

```
      D2=1.
      D3=1.
      D4=1.
      P1= 180
      P2= 0
      P3= 180
      A = 1.
      B = 0.
      C = 0.
C
C-----------------------------------------------------------------------
C                          MAIN PROGRAM
C-----------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
      DO 200 I=-90,0
         TH=I*P4
         DO 100 PHI=1,360,4
            PH=PHI*P4
            W1=K*D1*SIN(PH)*SIN(TH)
            W2=K*D2*SIN(PH)*SIN(TH)-P5
            W3=K*D3*SIN(TH)*COS(PH)-P6
            W4=K*D4*SIN(TH)*COS(PH)+P7
            W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
            G=SIN(W1)-A*SIN(W2)-B*SIN(W3)+C*SIN(W4)
            H=SQRT(W*W+G*G)/(1+A+B+C)
            Z(PHI)=20*ALOG10(H)
            IF(Z(PHI).LE.-40.) THEN
               Z(PHI)=0.
            ELSE
               Z(PHI)=Z(PHI)
            END IF
            R=40.+Z(PHI)
            P= FLOAT(PHI)
            T=FLOAT(I)
            X=R*COS(TH)*COS(PH)+40.
            Y=R*COS(TH)*SIN(PH)+40.
            ZM=-R*SIN(TH)
            WRITE(8,1) X,Y,ZM
1          FORMAT(2X,3(E10.3,5X))
           CALL GETMAT(X,Y,ZM,1,0)
100      CONTINUE
200   CONTINUE
C
C-----------------------------------------------------------------------
C          A PROGRAM FOR PLOTTING BY SHERPAOR BY TEK618
C-----------------------------------------------------------------------
C
      CALL ENDMAT(ZMM,0)
      CALL SURMAT (ZMM,1,90,1,90,0)
      CALL DASH
      CALL MARKER(17)
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL SURVIS('BOTTOM')
      CALL MESSAG('DIRECTIVITY PATTERN$',19,2.0,-.5)
      CALL RESET('COMPLX')
      CALL RESET('HEIGHT')
c
c
------------------------------------------------------------------------
                    PROGRAM FOR THE LOWER HEMISPHERE
------------------------------------------------------------------------
c
C
      CALL BGNMAT(90,90)
C-----------------------------------------------------------------------
C                        INPUT PARAMETERS
C-----------------------------------------------------------------------
C
      PI=3.1415917
      K=PI
      D1=1.
      D2=1.
```

```
      D3=1.
      D4=1.
      P1= 180
      P2= 0
      P3= 180
      A = 1.
      B = 0.
      C = 0.
C
C-----------------------------------------------------------------------
C                              MAIN PROGRAM
C-----------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
      DO 250 I=-180,-90
         TH=I*P4
         DO 150 PHI=1,360,4
            PH=PHI*P4
            W1=K*D1*SIN(PH)*COS(TH)
            W2=K*D2*SIN(PH)*COS(TH)+P5
            W3=K*D3*SIN(TH)*COS(PH)-P6
            W4=K*D4*SIN(TH)*COS(PH)+P7
            W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
            G=SIN(W1)-A*SIN(W2)+B*SIN(W3)-C*SIN(W4)
            H=SQRT(W*W+G*G)/(1+A+B+C)
            Z(PHI)=20*ALOG10(H)
            IF(Z(PHI).LE.-40.) THEN
               Z(PHI)=0.
            ELSE
               Z(PHI)=Z(PHI)
            END IF
            R=40.+Z(PHI)
            P= FLOAT(PHI)
            T=FLOAT(I)
            X=R*COS(TH)*COS(PH)+40.
            Y=R*COS(TH)*SIN(PH)+40.
            ZM=R*SIN(TH)
            WRITE(8,1) X,Y,ZM
1          FORMAT(2X,3(E10.3,5X))
           CALL GETMAT(X,Y,ZM,1,0)
150     CONTINUE
250   CONTINUE
      CALL ENDMAT(ZMM,0)
      CALL SURMAT (ZMM,1,90,1,90,0)
      CALL DASH
      CALL MARKER(17)
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL SURVIS('BOTTOM')
      CALL ENDPL(0)
      CALL DONEPL
CHECKSUM=012362
      STOP
      END
```

APPENDIX D

PROGRAM FOR THE 3-DIMENSIONAL GRAPH USING VECTOR DRAWING MET

```
**********************  INFORMATION  *******************************
*                                                                   *
*        THE OBJECTIVE OF THIS PROGRAM IS TO CALCULATE AND DRAW     *
*        THE DIRECTIVITY PATTERN IN THREE-DIMENSION.                *
*        THE DRAWING METHOD IS THE VECTOR DRAWING METHOD OF DISSPLA. *
*                                                                   *
*********************  VARIABLE DEFINITION  ************************
*                                                                   *
*        Z : DIRECTIVITY IN dB                                      *
*        XT  : "TO" POINT OF X IN DRAWING VECTOR                    *
*        YT  : "TO" POINT OF Y IN DRAWING VECTOR                    *
*        ZT  : "TO" POINT OF Z IN DRAWING VECTOR                    *
*        XF  : "FROM" POINT OF X IN DRAWING VECTOR                  *
*        YF  : "FROM" POINT OF Y IN DRAWING VECTOR                  *
*        ZF  : "FROM" POINT OF Z IN DRAWING VECTOR                  *
*        P1 : PHASE (DEGREE) OF SOURCE A                            *
*        P2 : PHASE (DEGREE) OF SOURCE B                            *
*        P3 : PHASE (DEGREE) OF SOURCE C                            *
*        P4 : VARIABLE TO CHANGE DEGREE TO RADIAN                   *
*        P5 : RADIAL VALUE OF P1                                    *
*        P6 : RADIAL VALUE OF P2                                    *
*        P7 : RADIAL VALUE OF P3                                    *
*        K : WAVE NUMBER                                            *
*        D1 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE 1  *
*        D2 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE A  *
*        D3 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE B  *
*        D4 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE C  *
*        PHI  : PHI IN DEGREE                                       *
*        I : THETA IN DEGREE                                        *
*        PH : PHI IN RADIAN                                         *
*        TH : THETA IN RADIAN                                       *
*        PI : 3.1415917                                             *
*                                                                   *
*********************  VARIABLE DECLARATION  ***********************
      REAL R,Z,XT,YT,XF,YF,ZF,ZT,a,b,c
      REAL P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI
      INTEGER PHI,P1,P2,P3,I
C
C*****************************************************************
      DIMENSION Z(0:2500),ZMM(46,46),V(2000),U(2000)
      REAL P,T,R,X,Y,ZM,ZZM,A,B,C,V,U
      REAL P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI
      INTEGER PHI,P1,P2,P3,I,S
C
C-------------------------------------------------------------------
C                          INPUT PARAMETERS
C-------------------------------------------------------------------
C
      PI=3.1415917
      K=10.55
      D1=0.5
      D2=0.5
      D3=0.5
      D4=0.5
      P1= 0
      P2=180
      P3=180
      A = 1.
      B = 1.
      C = 1.
C
C-------------------------------------------------------------------
C                           MAIN PROGRAM
C-------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
      S=1
```

```
      DO 200 I=0,90
         TH=I*P4
         DO 100 PHI=0,180
            PH=PHI*P4
            W1=K*D1*SIN(PH)*SIN(TH)
            W2=K*D2*SIN(PH)*SIN(TH)-P5
            W3=K*D3*SIN(TH)*COS(PH)-P6
            W4=K*D4*SIN(TH)*COS(PH)+P7
            W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
            G=SIN(W1)-A*SIN(W2)-B*SIN(W3)+C*SIN(W4)
            H=SQRT(W*W+G*G)/(1+A+B+C)
            Z(PHI)=20*ALOG10(H)
            IF((Z(PHI) .GT.-10.).AND.(Z(PHI).LT.-9.)) THEN
               Z(PHI)= -30.
            ELSE
               Z(PHI)= Z(PHI)
            END IF
            ZM=Z(PHI)
C              WRITE(8,1) I,PHI,ZM
            IF (ZM .EQ. -30.) THEN
               V(S) = FLOAT (PHI)
               U(S) = FLOAT (I)
C            WRITE(8,1) V(S),U(S),ZM
               S=S+1
            END IF
C           WRITE(8,1) I,PHI,Z
C1         FORMAT(2X,2(I3,5X),F10.5)
C           WRITE(8,1) AX(L),BY(L),ZM
C1         FORMAT(2X,3(F10.3,5X))
100      CONTINUE
200   CONTINUE
C
C-----------------------------------------------------------------------
C           A PROGRAM FOR PLOTTING BY SHERPA OR BY TEK618
C-----------------------------------------------------------------------
C
      CALL MEDBUF
C     CALL COMPRS
      CALL TEK618
      CALL PHYSOR(1.,1.)
      CALL PAGE(15.5,12.)
      CALL AREA2D(10.5,9.1)
      CALL FRAME
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL XNAME('PHI(DEG)  $',10)
      CALL YNAME('THETA(DEG)$',10)
      CALL YTICKS(2)
      CALL XTICKS(4)
      CALL GRAF(0,20,180,0,10,90)
      CALL CURVE(V,U,S,-1)
      CALL MESSAG('THETA=25 DEGREE',15,11.,8.5)
      CALL MESSAG('K=5.5',5,11.,8.2)
      CALL MESSAG('D1=1. D2=1.',11,11.,7.9)
      CALL MESSAG('D3=1. D4=1.',11,11.,7.6)
      CALL MESSAG('P2=180 P3=0 P4=180',18,11.,7.3)
      CALL MESSAG('A=1. B=1. C=1.',14,11.,7.0)
      CALL RESET('HEIGHT')
      CALL HEIGHT(.4)
      CALL MESSAG('TRACK(-20.DB)',13,3.1,9.8)
      CALL RESET('ALL')
      CALL NOCHEK
      CALL ENDGR(0)
      CALL PHYSOR(11.85,7.6)
      CALL AREA2D(3.5,2.5)
      CALL FRAME
      CALL ENDPL(0)
      STOP
      END
```

APPENDIX E

P3D

```
***********************  INFORMATION  ********************************
*                                                                    *
*        THE OBJECTIVE OF THIS PROGRAM IS TO CALCULATE AND DRAW      *
*        THE DIRECTIVITY PATTERN IN THREE-DIMENSION.                 *
*        THE DRAWING METHOD IS THE SUBROUTINE SURMAT OF DISSPLA      *
*        ABOUT θ-Φ PLANE.                                            *
*                                                                    *
**********************  VARIABLE DEFINITION  *************************
*                                                                    *
*        Z : DIRECTIVITY IN dB                                       *
*        ZMM : DOUBLE MATRIX TO GET θ-Φ plane                        *
*        X : DUMMY VARIABLE OF THETA                                 *
*        Y : DUMMY VARIABLE OF PHI                                   *
*        ZM : DUMMY VARIABLE OF DIRECTIVITY                          *
*        P1 : PHASE (DEGREE) OF SOURCE A                             *
*        P2 : PHASE (DEGREE) OF SOURCE B                             *
*        P3 : PHASE (DEGREE) OF SOURCE C                             *
*        P4 : VARIABLE TO CHANGE DEGREE TO RADIAN                    *
*        P5 : RADIAL VALUE OF P1                                     *
*        P6 : RADIAL VALUE OF P2                                     *
*        P7 : RADIAL VALUE OF P3                                     *
*        K : WAVE NUMBER                                             *
*        D1 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE 1   *
*        D2 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE A   *
*        D3 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE B   *
*        D4 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE C   *
*        PHI : PHI IN DEGREE                                         *
*        I : THETA IN DEGREE                                         *
*        PH : PHI IN RADIAN                                          *
*        TH : THETA IN RADIAN                                        *
*        PI : 3.1415917                                              *
*                                                                    *
**********************  VARIABLE DECLARATION  ************************
      DIMENSION Z(2500),ZMM(46,46)
      REAL X,Y,ZM,P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI
      real a,b,c
      INTEGER PHI,P1,P2,P3,I
C
C---------------------------------------------------------------------
C           A PROGRAM FOR PLOTTING BY SHERPAOR BY TEK618
C---------------------------------------------------------------------
C
      CALL COMPRS
C     CALL TEK618: MOVE C TO THE UPPER LINE WHEN DRAWING WITH TEK618
      CALL RESET (3HALL)
      CALL PHYSOR(0.5,1.)
      CALL PAGE(15.5,12.)
      CALL SCMPLX
      CALL AREA2D(10.5,9.15)
      CALL X3NAME('THETA(DEGREE)',13)
      CALL Y3NAME('PHI(DEGREE)',11)
      CALL Z3NAME('DIRECTIVITY(DB)',15)
      CALL VOLM3D (17.,17.,17.)
      CALL VUANGL(+20.,+20.,500.)
      CALL INTAXS
      CALL ZAXANG (-90.)
      CALL GRAF3D(0.,5.,90.,180.,6.,360.,-40.,2.,0.)
      CALL BLSUR
      CALL BGNMAT(46,46)
C
C---------------------------------------------------------------------
C                        INPUT PARAMETERS
C---------------------------------------------------------------------
C
      PI=3.1415917
      K=5.5
      D1=1.
      D2=1.
      D3=1.
      D4=1.
```

```
      P1= 180
      P2= 0
      P3= 180
      A = 1.
      B = 1.
      C = 1.
C
C-----------------------------------------------------------------------
C                          MAIN PROGRAM
C-----------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
      DO 200 I=0,90,2
         TH=I*P4
         DO 100 PHI=180,360,4
            PH=PHI*P4
            W1=K*D1*SIN(PH)*SIN(TH)
            W2=K*D2*SIN(PH)*SIN(TH)-P5
            W3=K*D3*SIN(TH)*COS(PH)-P6
            W4=K*D4*SIN(TH)*COS(PH)+P7
            W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
            G=SIN(W1)-A*SIN(W2)-B*SIN(W3)+C*SIN(W4)
            H=SQRT(W*W+G*G)/(1+A+B+C)
            Z(PHI)=20*ALOG10(H)
            IF(Z(PHI).LE.-40.) THEN
               Z(PHI)=-40.
            ELSE
               Z(PHI)= Z(PHI)
            END IF
            X=I
            Y=PHI
            ZM=Z(PHI)
            WRITE(8,1) X,Y,ZM
1           FORMAT(2X,3(E10.3,5X))
           CALL GETMAT(X,Y,ZM,1,0)
100      CONTINUE
200   CONTINUE
C
C-----------------------------------------------------------------------
C          A PROGRAM FOR PLOTTING BY SHERPAOR BY TEK618
C-----------------------------------------------------------------------
C
      CALL ENDMAT(ZMM,0)
      CALL SURMAT (ZMM,1,46,1,46,0)
      CALL DASH
      CALL MARKER(17)
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL SURVIS('BOTTOM')
      CALL MESSAG('K=5.5',5,11.,8.5)
      CALL MESSAG('D1=1. D2=1.',11,11.,8.2)
      CALL MESSAG('D3=1. D4=1.',11,11.,7.9)
      CALL MESSAG('VIEW ANGLE= 20, 20',18,11.,7.6)
      CALL MESSAG('P2=180 P3=0 P4=180',18,11.,7.3)
      CALL MESSAG('A=1. B=1. C=1.',14,11.,7.0)
      CALL RESET('HEIGHT')
      CALL HEIGHT(.4)
      CALL MESSAG('DIRECTIVITY PATTERN',19,3.05,9.8)
      CALL ENDGR(0)
      CALL PHYSOR(11.35,7.6)
      CALL AREA2D(3.5,2.5)
      CALL FRAME
      CALL DONEPL
CHECKSUM=012362
      STOP
      END
```

APPENDIX F
TRACE

```
**********************  INFORMATION  *********************************
*                                                                     *
*       THE OBJECTIVE OF THIS PROGRAM IS TO CALCULATE AND DRAW        *
*       THE CONSTANT dB LEVEL OF THE THREE-DIMENSIONAL PLOT.          *
*       THE DRAWING METHOD IS THE SUBROUTINE CURVE OF DISSPLA.        *
*                                                                     *
*********************  VARIABLE DEFINITION  **************************
*                                                                     *
*       Z : DIRECTIVITY IN dB                                         *
*       v : ARRAY TO TRACK Φ                                          *
*       u : ARRAY TO TRACK θ                                          *
*       P1 : PHASE (DEGREE) OF SOURCE A                               *
*       P2 : PHASE (DEGREE) OF SOURCE B                               *
*       P3 : PHASE (DEGREE) OF SOURCE C                               *
*       P4 : VARIABLE TO CHANGE DEGREE TO RADIAN                      *
*       P5 : RADIAL VALUE OF P1                                       *
*       P6 : RADIAL VALUE OF P2                                       *
*       P7 : RADIAL VALUE OF P3                                       *
*       K : WAVE NUMBER                                               *
*       D1 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE 1     *
*       D2 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE A     *
*       D3 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE B     *
*       D4 : DISTANCE FROM THE GEOMETRICAL CENTER TO THE SOURCE C     *
*       PHI : PHI IN DEGREE                                           *
*       I : THETA IN DEGREE                                           *
*       PH : PHI IN RADIAN                                            *
*       TH : THETA IN RADIAN                                          *
*       PI : 3.1415917                                                *
*                                                                     *
*********************  VARIABLE DECLARATION  *************************
      DIMENSION Z(0:2500),ZMM(46,46),V(2000),U(2000)
      REAL P,T,R,X,Y,ZM,ZZM,A,B,C,V,U
      REAL P4,P5,P6,P7,W1,W2,W3,W4,W,G,H,K,D1,D2,D3,D4,PH,TH,PI
      INTEGER PHI,P1,P2,P3,I,S
C
C----------------------------------------------------------------------
C                          INPUT PARAMETERS
C----------------------------------------------------------------------
C
      PI=3.1415917
      K=10.55
      D1=0.5
      D2=0.5
      D3=0.5
      D4=0.5
      P1= 0
      P2=180
      P3=180
      A = 1.
      B = 1.
      C = 1.
C
C----------------------------------------------------------------------
C                           MAIN PROGRAM
C----------------------------------------------------------------------
C
      P4=PI/180
      P5=P1*P4
      P6=P2*P4
      P7=P3*P4
      S=1
      DO 200 I=0,90
         TH=I*P4
         DO 100 PHI=0,180
            PH=PHI*P4
            W1=K*D1*SIN(PH)*SIN(TH)
            W2=K*D2*SIN(PH)*SIN(TH)-P5
            W3=K*D3*SIN(TH)*COS(PH)-P6
            W4=K*D4*SIN(TH)*COS(PH)+P7
            W=COS(W1)+A*COS(W2)+B*COS(W3)+C*COS(W4)
```

```
            G=SIN(W1)-A*SIN(W2)-B*SIN(W3)+C*SIN(W4)
            H=SQRT(W*W+G*G)/(1+A+B+C)
            Z(PHI)=20*ALOG10(H)
            IF((Z(PHI) .GT.-10.).AND.(Z(PHI).LT.-9.)) THEN
               Z(PHI)= -30.
            ELSE
               Z(PHI)= Z(PHI)
            END IF
            ZM=Z(PHI)
C             WRITE(8,1) I,PHI,ZM
            IF (ZM .EQ. -30.) THEN
               V(S) = FLOAT (PHI)
               U(S) = FLOAT (I)
C            WRITE(8,1) V(S),U(S),ZM
               S=S+1
            END IF
C           WRITE(8,1) I,PHI,Z
C1         FORMAT(2X,2(I3,5X),F10.5)
C           WRITE(8,1) AX(L),BY(L),ZM
C1         FORMAT(2X,3(F10.3,5X))
100      CONTINUE
200   CONTINUE
C
C-----------------------------------------------------------------------
C           A PROGRAM FOR PLOTTING BY SHERPA OR BY TEK618
C-----------------------------------------------------------------------
C
      CALL MEDBUF
C     CALL COMPRS;MOVE C TO TEK619 TO PRINT USING SHERPA
      CALL TEK618
      CALL PHYSOR(1.,1.)
      CALL PAGE(15.5,12.)
      CALL AREA2D(10.5,9.1)
      CALL FRAME
      CALL COMPLX
      CALL HEIGHT(.2)
      CALL XNAME('PHI(DEG)  $',10)
      CALL YNAME('THETA(DEG)$',10)
      CALL YTICKS(2)
      CALL XTICKS(4)
      CALL GRAF(0,20,180,0,10,90)
      CALL CURVE(V,U,S,-1)
      CALL MESSAG('THETA=25 DEGREE',15,11.,8.5)
      CALL MESSAG('K=5.5',5,11.,8.2)
      CALL MESSAG('D1=1. D2=1.',11,11.,7.9)
      CALL MESSAG('D3=1. D4=1.',11,11.,7.6)
      CALL MESSAG('P2=180 P3=0 P4=180',18,11.,7.3)
      CALL MESSAG('A=1. B=1. C=1.',14,11.,7.0)
      CALL RESET('HEIGHT')
      CALL HEIGHT(.4)
      CALL MESSAG('TRACK(-20.DB)',13,3.1,9.8)
      CALL RESET('ALL')
      CALL NOCHEK
      CALL ENDGR(0)
      CALL PHYSOR(11.85,7.6)
      CALL AREA2D(3.5,2.5)
      CALL FRAME
      CALL ENDPL(0)
      STOP
      END
```

APPENDIX G
LIST OF COMPUTER OUTPUT

• SAMPLE CASE 1

A	B	C	K	D_1	D_2	D_3	D_4	φ_2	φ_3	φ_4	Φ	θ	H	F
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	31	0.955567	-0.394776
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	32	0.970322	-0.261679
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	33	0.982069	-0.157164
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	34	0.990826	-0.080049
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	35	0.996641	-0.029226
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	36	0.999579	-0.003656
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	37	0.999728	-0.002363
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	38	0.997193	-0.024419
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	39	0.992094	-0.068947
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	40	0.984566	-0.135104
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	41	0.974756	-0.222079
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	42	0.962821	-0.329093
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	41	0.948922	-0.455388
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	44	0.933230	-0.600225
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	45	0.915917	-0.762881
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	46	0.897156	-0.942645
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	47	0.877121	-1.138807
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	48	0.855985	-1.350672
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	49	0.833918	-1.577533
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	50	0.811083	-1.818697
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	81	0.261312	-11.656804
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	82	0.255355	-11.857100
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	83	0.250133	-12.036570
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	84	0.245633	-12.194245
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	85	0.241845	-12.329250
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	86	0.238759	-12.403822
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	87	0.236367	-12.528270
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	88	0.234663	-12.591125
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	89	0.233642	-12.628973
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	90	0.233302	-12.641622
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	91	0.233642	-12.628973
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	92	0.234663	-12.591125
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	93	0.236367	-12.528270
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	94	0.238759	-12.440822
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	95	0.241845	-12.329267
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	96	0.245633	-12.194263
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	97	0.250133	-12.036578
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	98	0.255355	-11.857116
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	99	0.261311	-11.656837
1.0	1.0	1.0	10.55	0.50	0.50	0.50	0.50	0	180	180	0	100	0.268014	-11.436835

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